Nuclear Levels Excited by Inelastic Neutron Scattering*

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Gamma-ray, neutron, and gamma-gamma coincidence spectra have been obtained from inelastic interactions of 2.48-Mev neutrons with P^{31}, Mn^{55}, Co^{59}, As^{75}, Nb^{93}, and Bi^{209}. The following previously unreported gamma rays have been observed: Co^{59} 2.11±0.05, 0.698±0.015, 0.559±0.022, 0.132±0.010 Mev; As^{75} 1.81±0.04, 1.61±0.04, 1.32±0.04 Mev; Nb^{93} 2.11±0.08, 1.94±0.07, 1.52±0.04, 0.345±0.017 Mev. Evidence has been found for the existence of a 1.56±0.03 Mev level in Mn^{55} and possibly a 1.02±0.05 Mev level in As^{75}. The following previously unreported coincidences have been observed: Co^{59} 0.132−2.11 Mev; and As^{75} 0.578−0.136 Mev.

INTRODUCTION

SEVERAL different methods for using inelastic neutron scattering to study the excited states of nuclei have been used by previous investigators. These methods include (1) investigation of the gamma radiation emitted during the de-excitation of the scattering nuclei,[1–3] (2) determination of the energies of the inelastically scattered neutrons,[4,5] and (3) determination of the threshold neutron energies necessary for the excitation of specific nuclear levels.[6,7] The first method is useful in that the energies of the radiations correspond directly to the energy differences between levels. Ambiguities in this method appear when questions of fitting the observed gamma rays into a consistent level scheme arise and when there is doubt that a gamma ray is in fact the result of an inelastic neutron scattering event. The first type of ambiguity can often be resolved by use of coincidence techniques for establishing the existence of possible cascade radiations in the de-excitation process.

In many cases the ambiguities concerning the origin of gamma radiations can be clarified by resort to the second method. Provided that the incident neutrons are approximately monoenergetic, energy determinations of the incident and inelastically scattered neutrons suffice to fix the level energies. When gamma radiations having energies consistent with the de-excitation of these levels are observed, some confidence in the supposed production mode is warranted. Of course a coincidence experiment relating an inelastically scattered neutron group directly to the appropriate gamma radiation is most convincing; a limited number of such experiments have been performed.[8,9]

Partly because of the difficulties of measuring the energies of the inelastically scattered neutrons precisely, the third method has been of considerable use in establishing both the existence of excited states and their energies.

The purpose of the present investigation is to re-examine, by use of the first two methods, a selected group of previously studied nuclei in the hope of clarifying uncertainties in energy and decay modes and of providing evidence for any new levels which might be observed.

EXPERIMENTAL PROCEDURE

A direct-current, two-gap, linear accelerator capable of delivering a 150-μa beam of deuterons at energies from 30 kev to 150 kev was used. After acceleration, the deuterons passed down a 4-ft length of 1.25-inch diameter thin-walled aluminum tubing to strike an occluded deuterium target built up on a 0.007-inch air-cooled aluminum backing. Neutrons were produced by the $D(d,n)He^3$ reaction. The neutrons were produced and scattered at a position considerably removed from the accelerator vacuum pumps and other massive objects.

The choice of scatterers was determined by questions of isotopic purity, availability and cost. Of those selected the results from phosphorus, manganese, cobalt, arsenic, niobium, and bismuth are of sufficient interest to be reported below. The amounts of scatterer used varied from about 1.1 moles to 5.7 moles. The scatterers were in the shape of right cylinders. Solid materials were used where possible, but powdered forms were also utilized. Powdered scatterers were enclosed in 0.001-inch aluminum foil containers. Table I gives a resume of the characteristics of the scatterers used and includes for scatterers enclosed in aluminum foil the molar percentage of aluminum present due to the wrapping.

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[1] Scherrer, Allison, and Faust, Phys. Rev. **96**, 386 (1954).
[2] J. J. Van Loef and D. A. Lind, Phys. Rev. **101**, 103 (1956).
[3] R. B. Day, Phys. Rev. **102**, 767 (1956).
[4] Eliot, Hicks, Beghian, and Halban, Phys. Rev. **94**, 144 (1954).
[5] L. Cranberg and J. S. Levin, Phys. Rev. **103**, 343 (1956).
[6] R. M. Kiehn and C. Goodman, Phys. Rev. **95**, 989 (1954).
[7] J. B. Guernsey and A. Wattenberg, Phys. Rev. **101**, 1516 (1956).
[8] Garrett, Hereford, and Sloope, Phys. Rev. **91**, 441(A) (1953); **92**, 1507 (1953).
[9] Shapiro, Scherrer, Allison, and Faust, Phys. Rev. **95**, 751 (1954).

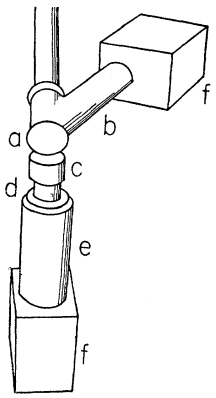

FIG. 1. Scattering geometry for gamma-ray experiments, showing: *a*, target; *b*, proton monitor; *c*, scatterer; *d*, scintillation crystal; *e*, photomultiplier tube; *f*, preamplifiers.

Three different types of experiments were performed in this investigation: (1) de-excitation gamma spectra were obtained, (2) coincidence studies of these gamma radiations were made, and (3) inelastic neutron energies were measured. Each of these types will be discussed in turn.

GAMMA-RAY SPECTRA

In order to obtain an accurate spectrum of the gamma rays following inelastic neutron scattering, it is necessary to differentiate between the radiation produced by scattering in nearby materials and that produced by the selected scatterer. Previous investigators have employed various differentiation schemes including subtraction,[4] shielding,[10] and a coincidence requirement.[8] The experiments reported here rely on the validity of performing a direct subtraction. None of the above techniques is completely successful.

The arrangement of scatterer and detector for obtaining the gamma spectra is shown in Fig. 1. The scatterer, sodium iodide detector, and type 6292 photomultiplier tube are along a line at 90° with respect to the incident deuteron beam. A proton scintillation detector is located within the vacuum system at 150° with respect to the incident deuterons. This detector serves as a monitor of the neutron production since the ratio of the cross sections for the two reactions $D(d,n)He^3$ and $D(d,p)H^3$ varies by less than 0.5% over the range of accelerating voltage experienced in any run.[11]

In the arrangement shown, neutrons interact with nuclei in the scatterer, producing gamma rays which may be detected by the sodium iodide scintillator. The scintillator also detects gamma rays produced by inelastic neutron scattering in the scintillation crystal itself, and by scattering in other adjacent matter. The gamma rays may conveniently be divided into four groups: (1) those originating in the scatterer, $N_s(E)$; (2) those originating in the detection crystal, $N_c'(E)$; (3) those originating in matter (e.g., the target) so placed that the radiation must traverse the scatterer to get to the detector, $N_t(E)$; and (4) those originating in other matter so placed that the radiation need not traverse the scatterer to get to the detector, $N_r(E)$. E refers to the gamma-ray energy. If $N(E)$ is the gamma spectrum detected with the scatterer in place, then

$$N(E)=\alpha_1(E)N_s(E)+\alpha_2(E)N_c(E)+\alpha_3(E)N_t(E)+N_r(E);$$

$\alpha_1(E)$ and $\alpha_3(E)$ take account of the attenuation and energy degradation of group (1) and group (3) gamma radiation, respectively, due to interaction of those radiations with the scatterer. Although the group (2) radiation is not modified before interacting with the detecting crystal, its spectrum has been written as $N_c'(E)=\alpha_2(E)N_c(E)$. In this way $\alpha_2(E)$ may be used to account for the modification of the group (2) gamma radiation caused by the attenuation and energy degradation, in the scatterer, of the neutrons which produce that radiation. With the scatterer removed $\alpha_2(E)=1$. In this discussion the energy degradation of the neutrons in the scatterer is neglected. Thus $\alpha_2(E)=\alpha_2$ is independent of energy. The determination of α_2 will be discussed presently.

If $N'(E)$ is the gamma spectrum detected with the scatterer removed, then

$$N'(E)=N_c(E)+N_t(E)+N_r(E).$$

Since $N_c(E)$ might reasonably be expected to be far larger than $N_r(E)$ and $N_t(E)$, due to the small amount of matter in the vicinity of the detection crystal relative to the amount in the crystal itself, the subtraction was performed in such a way as to eliminate $N_c(E)$. Thus

$$N(E)-\alpha_2N'(E)=\alpha_1(E)N_s(E)+[\alpha_3(E)-\alpha_2]N_t(E)+[1-\alpha_2]N_r(E).$$

The last two terms on the right-hand side of this expression were neglected since they are small for two reasons: $N_t(E)$ and $N_r(E)$ are themselves quite small[12]; $1-\alpha_2$ lies between 0.1 and 0.2; and $\alpha_3(E)-\alpha_2$ is of similar size, except at low E or for high-Z scatterers.

TABLE I. Properties of scatterers used.

Scatterer	Form	Purity (%)	Moles	Molar percentage aluminum
P	powder	99	5.7	1
Mn	powder	99.9	1.9	2
Co	solid metal	99	2.4	...
As	small lumps	99.5	1.4	2
Nb	powder	99.5	1.1	3
Bi	solid metal	99.95	1.6	...

[10] J. J. Van Loef, thesis, Utrecht, 1955 (unpublished).
[11] Arnold, Phillips, Sawyer, Stovall, and Tuck, Phys. Rev. **93**, 483 (1954).

[12] Generally in these experiments $N_t(E)/N_s(E)\lesssim 0.2$ and $N_r(E)/N_s(E)\lesssim 0.2$. An exception to this occurs below 50 kev, in which region $N_t(E)$ is large because of bremsstrahlung from the accelerator.

The difference spectrum $N(E)-\alpha_2 N'(E)$ may not correspond exactly to $\alpha_1(E)N_s(E)$ due to the following distortions which all arise from the neglected terms in the preceding equation: (1) errors in α_2 will result in humps or dips at energies corresponding to emissions from sodium and iodine, the materials comprising the scintillator; (2) the presence of $N_t(E)$ may cause (a) humps or dips at energies corresponding to emissions from aluminum, the target material, and (b) a dip at low energies where the bremsstrahlung occurs; and (3) the presence of $N_r(E)$ may cause humps at energies corresponding to emission from other material in the room, predominantly aluminum and iron. There was no evidence of effects 2(a) and 3; there was evidence of effects 1 and 2(b). Effect 2(b) could be partially reduced by placing a cylinder of carbon between target and crystal when the scatterer was removed. This was done when taking those spectra having a maximum gamma-ray energy of 0.2 Mev. The subtraction was modified to allow for the presence of the carbon.

The factor α_2 was determined by measuring the attenuation of incident neutrons by the scatterer. This was accomplished by recording the proton recoil spectra produced by the incident neutrons in a 0.5 cm thick anthracene crystal with and without the scatterer interposed between the target and the crystal. The ratio of the two spectra in a region representing nearly full neutron energy was taken as α_2. The value of α_2 varied from 0.833 to 0.928.

Three different gamma spectra were observed for each scatterer. One extended to a maximum gamma-ray energy of 2.5 Mev, a second spectrum was expanded to give a maximum energy of 0.6 Mev, and a third was further expanded to include only gamma rays to 0.2 Mev. A 2.5 cm by 2.5 cm right cylinder of sodium iodide was used in the 2.5-Mev and 0.6-Mev experiments and a 0.1 cm thick, 3.8 cm diameter crystal was used for the 0.2-Mev work. Deuteron accelerating voltages of 140, 130, and 50 kilovolts, respectively, were used in the three sets of experiments. All spectra were recorded on a Radiation Instrument Development Laboratory 100-channel pulse-height analyzer. The runs with scatterer removed and in place required roughly one-half hour each. The spectra were normalized by use of the proton monitor. Energy calibrations were made before and after each pair of runs. Analyzer linearity and zero were checked periodically with a mercury-relay pulse generator.

Energy calibration of the 2.5-Mev spectra used the 0.511-Mev annihilation radiation and 1.277-Mev gamma ray[13] from Na^{22} and the 0.695-Mev and 2.18-Mev radiations[14,15] from Pr^{144}.

Calibration of the 0.6-Mev spectra used the 0.511-Mev annihilation radiation from Na^{22}, the 0.134-Mev gamma ray[14,15] from Ce^{144}, the 0.205-Mev de-excitation gamma ray[2,16,17] from I^{127}, and a consistent peak in the total $N(E)$ spectra of each scatterer composed essentially of a superposition of the Compton edge due to the 0.63-Mev gamma ray in I^{127} and the 0.440-Mev photopeak in Na^{23}. The 0.205-Mev gamma ray of I^{127} was read from the $N(E)$ spectrum for each scatterer.

Calibration of the 0.2-Mev spectra used the 33.2-kev Cs^{137} x-ray, the 59.0-kev I^{127} gamma ray,[2,16,17] and the 127-kev Mn^{55} gamma ray.[18,19] The 59.0-kev I^{127} photopeak was read from the total spectrum $N(E)$ of all scatterers; the 127-kev Mn^{55} photopeak from the $N(E)$ spectrum of Mn^{55}.

The relative intensities of the radiations above 0.5-Mev energy from each scatterer were estimated, using a curve for photopeak efficiency due to Day.[3] No attempt was made to correct for self-absorption in the scatterer, (i.e., the nonconstancy of $\alpha_1(E)$).

COINCIDENCE SPECTRA

Gamma-gamma coincidence spectra were obtained using a scattering geometry differing from that shown in Fig. 1 in the following respects. The scatterer was again located at 90° with respect to the deuteron beam, but to one side rather than below. Two sodium iodide detectors were arranged directly above and below the scatterer. One detector utilized a 2.5 cm diameter, 2.5 cm high sodium iodide crystal, while the other utilized a 3.8 cm diameter, 3.8 cm high crystal except as specifically noted below.

The outputs of both detectors were fed *via* fast amplifiers into a fast-coincidence circuit having a resolving time of 60 mμsec. The output of the detector with the 3.8-cm by 3.8-cm crystal was fed *via* a nonoverloading amplifier into a single-channel pulse-height analyzer. The output of the detector with the 2.5-cm by 2.5-cm crystal was fed *via* a nonoverloading amplifier into the 100-channel pulse-height analyzer. The 100-channel pulse-height analyzer required a prompt and a delayed gating pulse to permit storage to occur. The output of the fast-coincidence circuit supplied the prompt gating pulse. The output of the single-channel pulse-height analyzer supplied the delayed gating pulse. The resolving time of the delayed gate circuit was 1.5 μsec. This pulse handling arrangement allowed all gamma rays to be recorded which were in coincidence with a gamma ray selected by the single-channel pulse-height analyzer. The random coincidence rate was found to be much smaller than the true coincidence rate, and was therefore ignored.

Calibration was carried out essentially as indicated for the gamma spectra.

[13] R. P. Leamer and G. W. Hinman, Phys. Rev. **96**, 1607 (1954).
[14] W. E. Kreger and C. S. Cook, Phys. Rev. **96**, 1276 (1954).
[15] Cork, Brice, and Schmid, Phys. Rev. **96**, 1295 (1954).
[16] Knight, Mize, Starner, and Barnes, Phys. Rev. **102**, 1592 (1956).
[17] Davis, Divatia, Lind, and Moffat, Phys. Rev. **103**, 1801 (1956).
[18] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[19] J. Freeman, Phil. Mag. **46**, 12 (1955).

In addition to the gamma-gamma coincidences arising from cascade decays in the scatterer, two undesired coincident events might be recorded: (1) Compton scattering events, in which a gamma ray was Compton-scattered in one crystal, and the scattered gamma ray was detected in the other crystal; (2) multiple inelastic scattering events, in which an inelastic neutron scattering occurred, the de-excitation gamma ray was detected in one crystal, and the neutron then produced a second gamma ray which was detected in the other crystal.

When the gamma ray which served as energy gate had an energy below 150 kev, the background coincident effects were eliminated as follows. The 3.8-cm by 3.8-cm NaI crystal was replaced by a 0.1-cm by 3.8-cm crystal. Two spectra were taken, one with no absorber between crystal and scatterer, and the other with 0.7 g/cm^2 of lead between the scatterer and the 0.1-cm thick crystal. The lead absorber should have had little effect on neutrons or high-energy gamma rays, but should have stopped most of the gamma rays of energies less than 150 kev. The difference between the spectrum taken without absorber and that taken with absorber was considered to be the gamma-ray spectrum in coincidence with the low-energy gamma ray.

When the gamma ray which served as energy gate had an energy in excess of 1 Mev, a lead absorber 3.3 g/cm^2 thick was placed between the scatterer and the 3.8-cm by 3.8-cm crystal to prevent back-scattered gamma rays from reaching the other crystal. (This was not done in the phosphorus experiment.)

The scattering geometry frequently prevented Compton-scattering events from being recorded. If a gamma ray were emitted from the scatterer and scattered from one crystal into the other, the scattered gamma ray would have less than 0.51 Mev energy, which was, in many cases, insufficient to trigger the energy gate. In a few cases, the scattering geometry was modified by moving the detection crystals back from the scatterer. This insured that a gamma ray Compton-scattered from one crystal to the other would have appreciably less than 0.51 Mev.

When the gamma ray which served as energy gate was more energetic than 150 kev, no precautions were taken to physically eliminate multiple inelastic scattering events, but care was taken in interpreting the data not to be misled by their presence.

Direct background subtractions with the scatterer removed were made when the gamma ray serving as energy gate was more energetic than 150 kev. The magnitudes of these subtractions were generally equivalent to that used in the gamma-ray spectra. The proton monitor was used for normalization purposes.

NEUTRON SPECTRA

The neutron spectra were obtained from interpretation of the proton recoil spectra produced in anthracene by the incident and scattered neutrons. These interpretations were made using the so-called ratio method introduced by Eliot, Hicks, Beghian, and Halban.[4] The ratio of the number of counts with scatterer in place to the number with scatterer removed may be plotted as a function of energy to yield steps corresponding to neutron energies. However, gamma-ray Compton edges as well as neutron groups appear as steps in the plot when this method is used; thus it is imperative to know the gamma spectra in order to interpret the ratio plot results.

The arrangement in the target area for the neutron measurements was identical to that employed in the gamma-ray experiments except that the proton monitor was omitted. Spectra obtained using a 0.5 cm thick, 3.7 cm diameter anthracene crystal were recorded by using the 100-channel analyzer.

Runs with and without the scatterer were of roughly one hour duration each. Calibration of the Compton edges was carried out using the Na^{22} radiations discussed above. These calibrations were made before and after each pair of runs. The neutron energies were calibrated with reference to the full energy of the neutron source as deduced from the (d,d) reaction energetics. A point halfway up on the leading edge of the proton spectrum was selected as this full energy and the calibration completed by use of relationships due to Birks.[20]

It must be said that satisfactory results were obtained only rarely, for (1) neutron groups either below 0.5 Mev or above 2.1 Mev could not be satisfactorily detected, (2) resolution was inadequate for separating closely spaced steps, and (3) statistical reliability more precise than the size of the effect (often less than 0.5%) was difficult to attain.

RESULTS

Phosphorus-31

The gamma-ray spectrum obtained from P^{31} contained three gamma rays at energies of 2.21±0.06, 1.27±0.015, and 0.95±0.03 Mev. Relative intensities were found to be 0.25±20%, 1.0±10%, and 0.35±25%, respectively.[21] The ratio plot shows two steps. One step corresponds to a neutron group at 1.95±0.05 Mev or to a gamma ray at 0.92±0.05 Mev and is therefore identified as the Compton edge from the 0.95-Mev gamma ray. A second step corresponds to a neutron energy of 1.30±0.08 Mev or to gamma rays at 0.56 ±0.04 Mev. Owing to the absence of gamma rays of energy near 0.56 Mev in the gamma-ray spectrum, this second step is identified with a neutron group and may be taken as evidence for the existence of a level at 1.18±0.08 Mev.

The coincidence data indicate the probable existence

[20] J. B. Birks, Proc. Phys. Soc. (London) **A64**, 847 (1951).

[21] The plus and minus attached to the 1.0 ratio is intended to reflect the uncertainty in the area of that photopeak and is not included in the uncertainties for the other peaks.

of a gamma ray at 1.00±0.05 Mev in coincidence with the 1.27-Mev gamma ray.

From these data, P^{31} would appear to have two levels below 2.5 Mev, one at 2.21 Mev and the other at 1.27 Mev. The 2.21-Mev level would appear to decay through the 1.27-Mev level 60% of the time and directly to the ground state 40% of the time. These results are in essential agreement with the $P^{31}(n,n')$ data of Cranberg and Levin,[5] who report a level at 1.25 Mev; the $Si^{30}(p,\gamma)$ data of Paul *et al.*,[22] who report levels at 1.26 and 2.23 Mev; and the $P^{31}(p,p')$ work of Van Patter *et al.*,[23] who report levels at 1.264 and 2.230 Mev, and of Endt and Paris,[24] who report levels at 1.267 and 2.234 Mev. It is probable that the 0.94-Mev transition between the 1.27- and 2.21-Mev levels is that reported at 1.0±0.04 Mev by Scherrer, Allison, and Faust.[1]

Manganese-55

The upper energy portion of the gamma spectrum from Mn^{55} is shown in Fig. 2; the complete spectrum contains the gamma rays listed with their relative intensities in Table II. No neutron spectrum was taken. The gamma-ray spectrum in coincidence with the 0.127-Mev transition is shown in Fig. 3. This spectrum shows gamma rays at 0.86, 1.18, and 2.23 Mev. The slight hump in the region from 1.5 to 1.6 Mev is too small by a factor of three to correspond to all of the 1.56-Mev transitions going *via* the 0.127-Mev level.

TABLE II. Gamma-ray energies and relative intensities[a] from Mn^{55}.

Energy (Mev)	Relative intensity	Energy (Mev)	Relative intensity
2.23±0.06	0.38±25%	1.18±0.02	0.69±10%
1.89±0.07	<0.27	0.86±0.01	1.0 ±10%
1.56±0.03	0.61±15%	0.127 calibration	...

[a] See reference 21.

These data suggest levels at 0.127, 0.99, 1.31, 1.56, 1.89, and 2.36 Mev. This result differs from the work of Beghian *et al.*[25] in that they place a 1.53-Mev transition above the 0.13 Mev to yield a level at 1.65 Mev. However, if the hump in our coincidence spectrum between 1.5 and 1.6 Mev does represent a 1.56 Mev −0.127 Mev cascade of low probability, the 1.65-Mev level of Beghian *et al.* may exist in addition to the 1.56-Mev level.

The levels suggested by the present data are to be compared with the results of $Mn^{55}(p,p')$ work by Hausmann *et al.*,[26] who report levels at 0.13, 1.00, 1.30, 1.56, 1.91, 2.27, and 2.42 Mev; and the $Mn^{55}(n,n')$ work of Cranberg and Levin,[5] who report levels at 0.98, 1.29, and 1.53 Mev.[27]

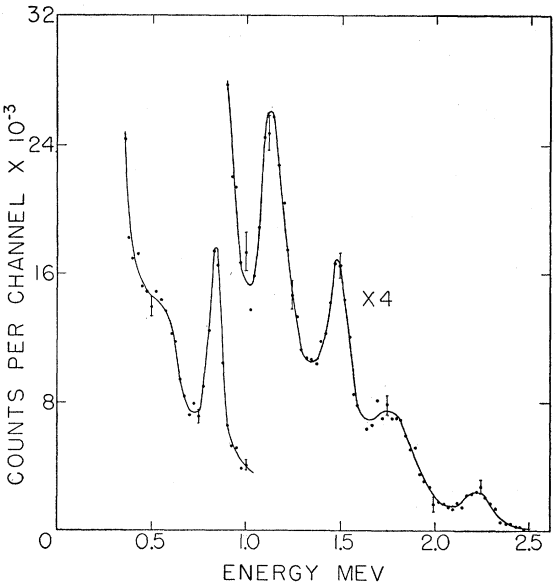

FIG. 2. Upper energy portion of Mn^{55} gamma spectrum.

Cobalt-59

Figure 4 shows the upper portion of the gamma-ray spectrum from Co^{59}. The gamma rays and their relative intensities are given in Table III. The neutron ratio plot gave evidence for unresolved neutron groups from 0.75 to 1.3 Mev.

The spectrum in coincidence with the 1.19-Mev radiation showed a probable peak at 0.56 Mev and the reverse experiment gave a 1.18-Mev peak of poor

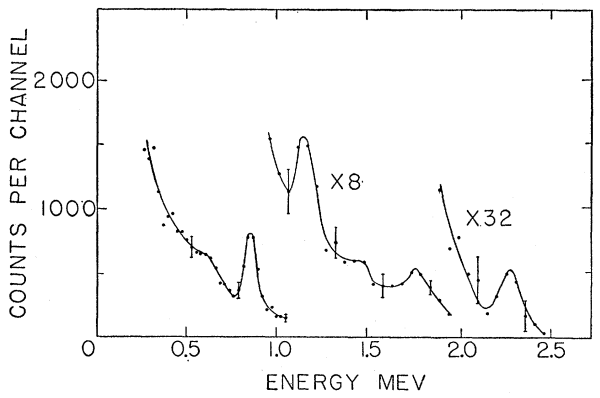

FIG. 3. Mn^{55} gamma spectrum in coincidence with the 0.127-Mev gamma ray.

[22] Paul, Bartholomew, Gove, and Litherland, Bull. Am. Phys. Soc. Ser. II, **1**, 39 (1956).
[23] Van Patter, Rothman, Porter, and Mandeville, Phys. Rev. **107**, 171 (1957).
[24] P. M. Endt and C. H. Paris, Phys. Rev. **106**, 764 (1957).
[25] Beghian, Hicks, and Milman, Phil. Mag. **1**, 261 (1956).
[26] Hausmann, Allen, Arthur, Bender, and McDole, Phys. Rev. **88**, 1296 (1952).
[27] *Note added in proof.*—The recent $Mn^{55}(p,p')$ results of Mazari, Sperduto, and Buechner, Phys. Rev. **108**, 103 (1957), indicate levels at 0.127, 0.983, 1.289, 1.527, and 1.884 Mev. They find no level at 1.65 Mev.

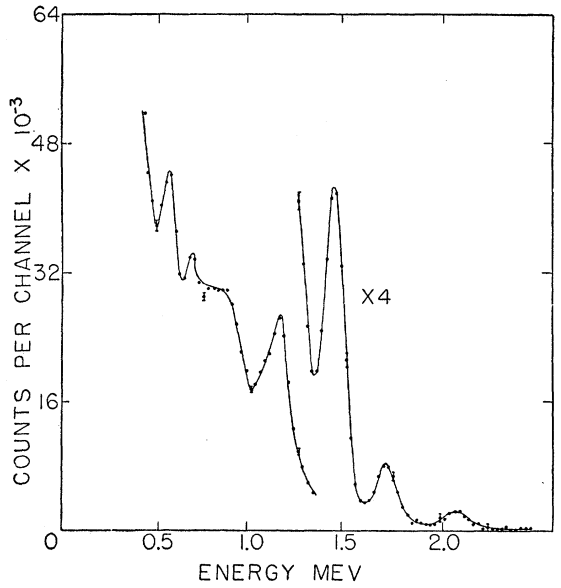

FIG. 4. Upper portion of the gamma spectrum of Co^{59}.

statistical accuracy in coincidence with the 0.56-Mev gamma rays. No gamma rays were found in coincidence with the 1.47-Mev radiation, but the statistical accuracy of this experiment was very low. The 2.11-Mev transition was found to be in coincidence with the 0.132-Mev radiation.

These data suggest levels at 1.19, 1.47, and 1.74 Mev, with the 0.559-Mev transition between the 1.19- and 1.74-Mev levels. The status of the 0.132-, 0.698-, and 2.11-Mev transitions remain uncertain from the present experiments alone. However, comparison with the recent $Co^{59}(p,p')$ work of Mazari *et al.*[28] suggests that the 2.11-Mev radiation corresponds to the total contribution to the spectrum of the levels from 2.061 to 2.205 Mev, that the 0.132-Mev radiation results from transitions among these levels, and that the 0.698-Mev gamma ray is a result of transitions from these upper levels to those levels between 1.43 and 1.48 Mev. These results differ from those deduced from other $Co^{59}(n,n')$ work,[5,29] only in the inclusion of levels in the neighborhood of 2.11 Mev.

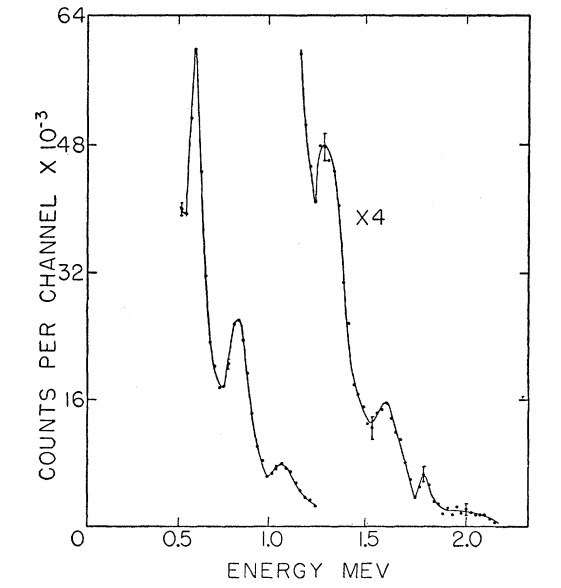

FIG. 5. Composite gamma spectrum of As^{75}.

TABLE III. Gamma-ray energies and relative intensities[a] from Co^{59}.

Energy (Mev)	Relative intensity	Energy (Mev)	Relative intensity
2.11±0.05	0.072±35%	0.698±0.015	0.060±30%
1.74±0.04	0.17 ±20%	0.559±0.022	0.14 ±20%
1.47±0.03	0.56 ±15%	0.132±0.010	...
1.19±0.02	1.0 ±20%		

[a] See reference 21.

Arsenic-75

A composite gamma-ray spectrum above 0.5 Mev from As^{75} is shown in Fig. 5. Table IV is a list of all the observed gamma-ray energies and their relative intensities. The ratio plot for the scatterer is shown in Fig. 6 and contains four steps. The alternative interpretations of these steps in terms of gamma-ray energies for Compton edges and neutron energies are given in Table V.

Since a reasonably strong 1.05-Mev photopeak is observed in the gamma spectrum and since a 0.199-Mev level is known to exist from radioactive decay data,[30] step (1) is probably due to both a neutron group and a gamma ray. Since no photopeaks are seen in the gamma spectra corresponding to steps (2) and (4), these may be interpreted as due to neutrons in spite of the absence of a step attributable to the 0.806-Mev gamma ray. However, the sloping character of the ratio plot to the left of step (3) and the absence of a distinct step corresponding to the 0.578-Mev gamma ray leads one to suppose that a gamma ray as well as a neutron group may be associated with this step.

TABLE IV. Gamma-ray energies and relative intensities[a] from As^{75}.

Energy (Mev)	Relative intensity	Energy (Mev)	Relative intensity
1.81 ±0.04	0.12±35%	0.578±0.015	0.76±20%
1.61 ±0.04	0.21±35%	0.275±0.015	...
1.32 ±0.04	0.8 ±25%	0.197±0.008	...
1.05 ±0.03	0.50±20%	0.127±0.006	...
0.806±0.025	1.0 ±20%		

[a] See reference 21.

[28] Mazari, Sperduto, and Buechner, Phys. Rev. **107**, 365 (1957).
[29] R. V. Smith, Bull. Am. Phys. Soc. Ser. II, **1**, 175 (1956).
[30] A. W. Schardt and J. Welker, Phys. Rev. **99**, 810 (1955).

TABLE V. Alternative interpretations of steps in the As^{75} ratio plot.

Step	Neutron energy (Mev)	Gamma energy (Mev)
(1)	2.27±0.08	1.02±0.04
(2)	1.90±0.05	0.86±0.03
(3)	1.46±0.08	0.62±0.03
(4)	1.11±0.09	0.47±0.03

Of the coincidence experiments performed, only a 0.578−0.135 Mev cascade was unambiguously identified. Failure of other experiments was probably due to interference from multiple inelastic neutron scattering as discussed under the coincidence procedures.

The results of Schardt and Welker[30] are helpful as indicating the possible relative positions of the low-energy transitions observed here. In particular, the 0.127-Mev transition we observed is probably a combination of their 0.136- and 0.121-Mev transitions which appear to go from their 0.402-Mev to their 0.265- and 0.280-Mev levels, respectively. Our 0.197-Mev transitions is undoubtedly the 0.199 Mev to ground state transition seen by Schardt and Welker and our 0.275-Mev radiation a composite of their 0.280 and 0.265 Mev to ground state transitions. Since the 0.578-Mev radiation is observed in coincidence with that at 0.135 Mev, a level at 0.980 Mev is suggested. Steps (3) and (4) of Table V correspond to levels at 1.02±0.08 and 1.37±0.09 Mev, respectively. Our levels compare poorly with those seen by Cranberg and Levin[5] at 0.78, 1.25, and 1.63 Mev in their $As^{75}(n,n')$ work.

Niobium-93

A composite gamma-ray spectrum from Nb^{93} is shown in Fig. 7. The gamma rays present and their relative intensities are given in Table VI. Ratio plots were made but only one step was sufficiently unambiguous to be useful. This step corresponds to a neutron energy of 1.45±0.05 Mev or the Compton edge of a gamma ray of 0.61±0.02 Mev. Since no gamma ray is seen near 0.61 Mev it is reasonable to interpret this step as due to neutrons leading to a level at 1.03±0.05 Mev. Coincidences were observed between the 0.345-Mev transition and the 0.95- and 0.73-Mev radiations. The 0.73-Mev transition was found to be in coincidence with radiations at 0.95 Mev and also with radiations from one or more of the three upper-energy gamma rays.

TABLE VI. Gamma-ray energies and relative intensities[a] from Nb^{93}.

Energy (Mev)	Relative intensity	Energy (Mev)	Relative intensity
2.11±0.08	0.04±55%	0.95 ±0.02	1.0 ±10%
1.94±0.07	0.07±45%	0.73 ±0.02	0.41±20%
1.52±0.04	0.15±15%	0.345±0.017	...

[a] See reference 21.

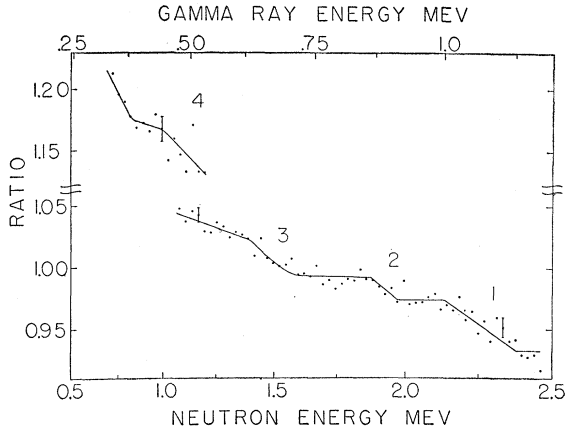

FIG. 6. Ratio plot for As^{75}.

Because of the previously mentioned possibility of interference from multiple inelastic scattering, these particular coincidence data do not warrant much confidence.

It is known from the work of Rothman *et al.*[31] that both a 0.957- and a 0.736-Mev transition go through the 29-kev metastable level to ground state. Scherrer *et al.*[1] have reported gamma rays at 0.270, 0.530, 0.690, and 0.910 Mev. The 2.08-, 1.94-, 1.51-, and 0.345-Mev gamma rays here reported appear not to have been previously observed.

The level from the ratio plot at 1.03 Mev is undoubtedly due to the cascaded 0.95- and 0.03-Mev transitions.

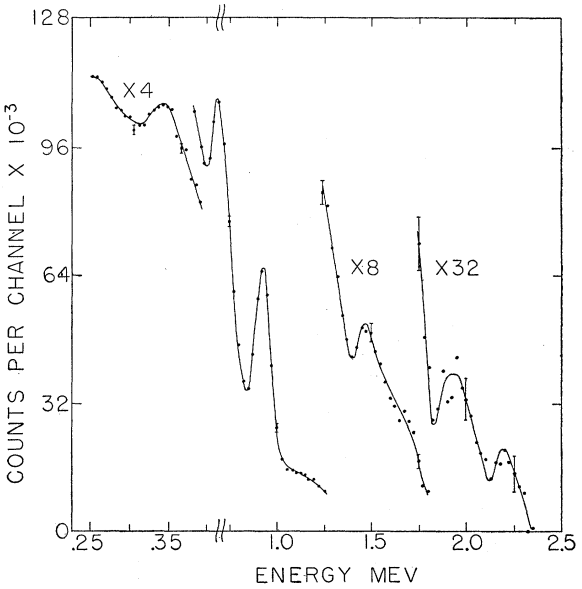

FIG. 7. Composite gamma spectrum of Nb^{93}.

[31] Rothman, Van Patter, Dubey, Porter, and Mandeville, Phys. Rev. **107**, 155 (1957).

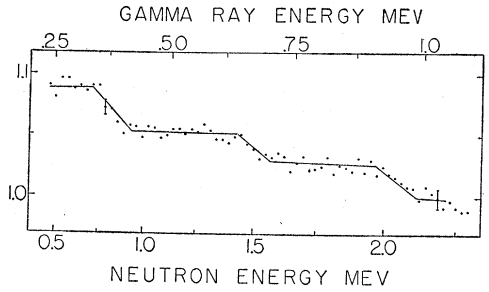

FIG. 8. Ratio plot for Bi^{209}.

Bismuth-209

Gamma rays from the de-excitation of Bi^{209} were observed at 1.66±0.05 and 0.899±0.022 Mev. The neutron ratio plot shown in Fig. 8 has steps at neutron energies of 1.49±0.06 and 0.80±0.07 Mev. These neutron energies correspond to levels at 0.99±0.06 and 1.68±0.07 Mev. Also present in the ratio plot is a step corresponding to the Compton edge of a 0.92±0.03 Mev gamma ray. No coincidence measurements were made.

The foregoing data suggest levels at 0.90±0.03 and 1.66±0.05 Mev; these levels have been observed by various other workers.[1,3–6,32]

A rather careful search was made in the region from 0.4 to 0.6 Mev in the gamma-ray spectra but no transition corresponding to the 0.46-Mev transition reported by Scherrer, Allison and Faust[1] or the 0.50-Mev isomeric state seen by Vegors and Axel[33] could be seen. Of course, detection in this region is made difficult by the 0.44-Mev photopeak in Na^{23} and the Compton edge due to the 0.63-Mev gamma ray in I^{127}.

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Decay of Tellurium-132†

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The decay of Te^{132} produced by fission of uranium has been investigated by using a scintillation spectrometer. In addition to the previously reported 0.23-Mev gamma ray and the iodine K x-ray, a 0.053-Mev gamma ray has been observed. Coincidence measurements permitted the determination of K-shell conversion coefficients for the two transitions. Probable decay schemes compatible with the observations are discussed.

THE seventy-five hour[1] beta decay of Te^{132} to I^{132} was first observed by Abelson.[2] In more recent experiments[3–5] the beta end-point energy has been found to be 0.22 Mev and a gamma ray of 0.23 Mev has been observed. Work in this laboratory has revealed, in addition, the presence of a 0.053-Mev gamma ray. The results obtained on the gamma spectra and various coincidence measurements are reported briefly in this paper.

Te^{132} was produced by bombarding an aqueous solution of uranyl acetate with neutrons obtained from the

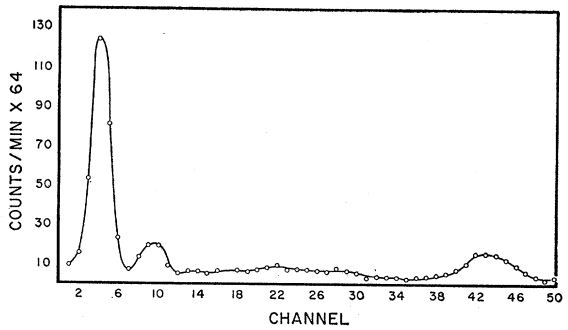

FIG. 1. Gamma-ray spectrum from Te^{132}, showing the 0.028-Mev iodine K x-ray and the 0.053-Mev and 0.23-Mev gamma rays.

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