Decay of 20-Minute Ag^{115}†

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A study of radiations from decay of 20-min Ag^{115} has led to determination of the maximum beta energy as 3.2±0.1 MeV and measurement of intensities of some eighteen γ rays ranging in energy from 0.13 to 2.50 MeV. Measurements via β-γ and γ-γ coincidence spectrometry and via Hoogenboom sum-coincidence spectrometry allowed construction of a tentative decay scheme. This scheme uses the ground state and seven excited levels of Cd^{115} also known from other studies via the $Cd^{114}(d,p)$ reaction. It is concluded that the 20-min Ag^{115} has spin and parity $\frac{1}{2}-$, with about half of the β decays being allowed transitions to states of spins and parities $\frac{1}{2}-$ or $\frac{3}{2}-$ at 2.12 and 2.50 MeV, the remainder being first-forbidden transitions to the ground-state and low-lying $\frac{1}{2}+$ and $\frac{3}{2}+$ levels. No evidence was found for radiations associated with branching to 43-day Cd^{115} (11/2−).

1. INTRODUCTION

THIS report describes the results of two simultaneous and independent studies of the decay of 20-min Ag^{115} through the techniques of scintillation spectroscopy. The results of these studies have been reported in preliminary form elsewhere.[1–3]

A 20-min silver activity was first observed among the products of the neutron-induced fission of U^{235} by Turkevich.[4] Later Duffield and Knight[5] produced what was presumed to be the same isotope by the (γ,p) reaction on cadmium enriched in Cd^{116}. Wahl and Bonner[6] established the mass number of the 20-min nuclide as 115, by observation of the growth of the radioactivity of 43-day and 53-h Cd^{115} from 20-min radio-silver separated from fission products. Their results indicated that, of the 20-min Ag^{115}, 9% decays to the 43-d metastable state and 91% decays to the 53-h ground state of Cd^{115}. They also showed that essentially all (more than 97%) of the 43-day cadmium isomer formed in fission grows from the 20-min silver, but that 28% of the 53-h ground-state Cd^{115} is formed by some other path. Since direct formation in the fission process of Cd^{115} was expected to be unimportant, they postulated the existence of a short-lived Ag^{115} isomer, which would decay only to 53-h cadmium with a half-life no longer than 3 min.

Alexander *et al.*[7] studied the radiations from the silver isotopes produced by the 15-MeV deuteron-induced fission of U^{238}, and reported that Ag^{115} decayed with a half-period of 21.1 min, and emitted beta particles with a maximum energy (measured by absorption methods) of 2.9±0.3 MeV. They also reported the presence of weak gamma rays, of 0.138±0.01 and 0.227±0.015 MeV, probably in coincidence.

They made direct studies of the decay of silver activity and the growth of Cd^{115} in spaced extractions of cadmium from silver samples, which gave an upper limit to the half-life of the short-lived silver isomer of 50 sec. By repeated rapid separation of Cd^{115} from samples of 45-sec Pd^{115} plus Ag^{115}, they deduced that the half-life of the short-lived isomer (designated as Ag^{115m}) was 20±10 sec. Any tendency for freshly formed Ag^{115} to accompany Cd^{115} in the chemical separation procedures employed would, however, shorten the apparent half-life of short-lived Ag^{115}. This value is therefore probably low, and we shall refer to the short-lived isomer as <50-sec Ag^{115}.

2. EXPERIMENTAL TECHNIQUES AND RESULTS

2.1. Source Preparation

The Ag^{115} studied in the present work was produced by (i) deuteron-induced fission of U^{238}, with targets of uranium metal foil of natural isotopic composition, and (ii) the fission of natural uranium in the form of uranyl nitrate by thermal neutrons.

Chemical separation of the silver activities from the fission-product mixture was achieved by means of conventional procedures.[8] The uranium foil was, for ex-

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[1] E. L. Bahn, Jr., Ph.D. thesis, Washington University, 1962 (unpublished).

[2] Discussion on Nuclear Chemistry, Oxford, 1962. Atomic Energy Research Establishment, Harwell, Report AERE M 1078, 1962 (unpublished).

[3] R. D. Fink, Ph.D. thesis, MIT, 1962 (unpublished).

[4] A. Turkevich, Argonne National Laboratory Report ANL 4010, 1947 (unpublished).

[5] R. B. Duffield and J. D. Knight, Phys. Rev. **75**, 1613 (1949).

[6] A. C. Wahl and N. A. Bonner, Phys. Rev. **85**, 570 (1952).

[7] J. M. Alexander, U. Schindewolf, and C. D. Coryell, Phys. Rev. **111**, 228 (1958).

[8] D. N. Sunderman and C. W. Townley, Nuclear Science Series, Report No. NAS-NS 3047 (National Academy of Sciences–National Research Council, Washington, D. C., 1961).

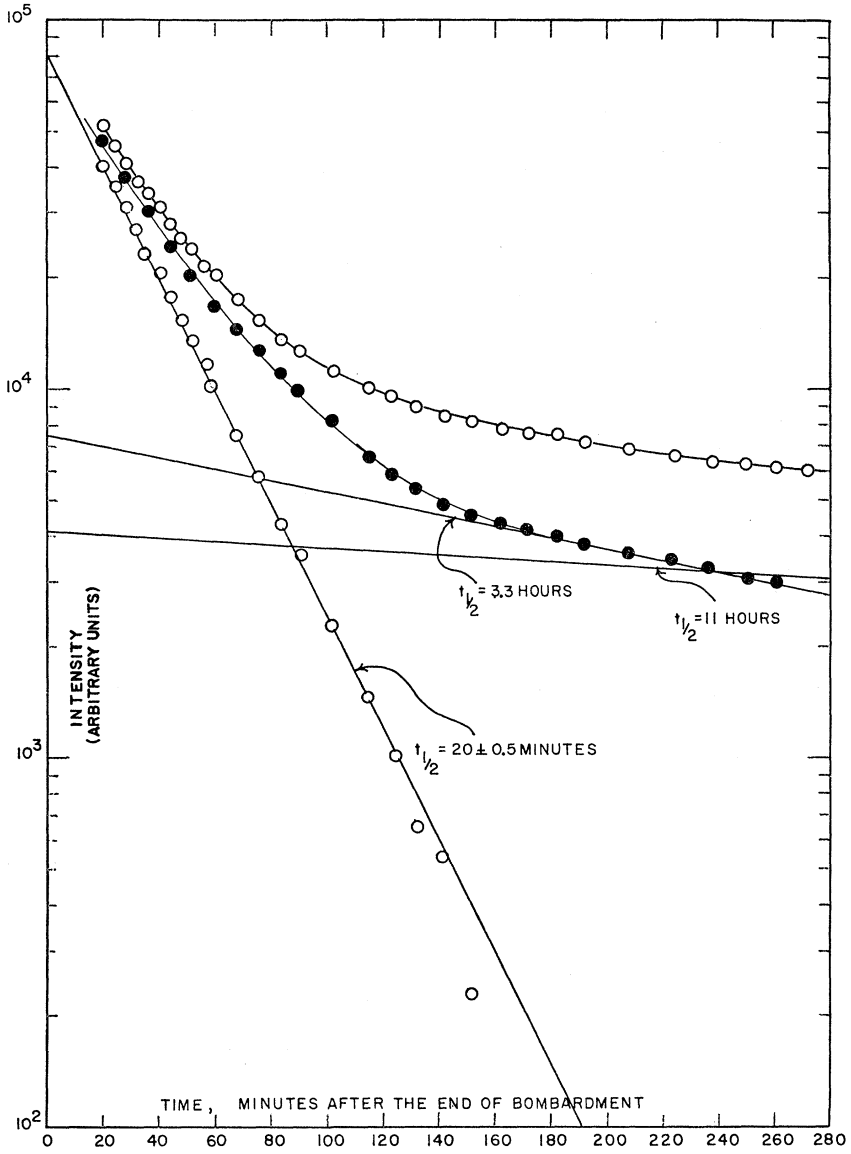

FIG. 1. Decay curve of the Ag^{115} gross beta activity of a separated sample of silver fission products.

ample, dissolved in aqua regia, and the silver precipitated successively as chloride, sulfide, and chloride, with a ferric hydroxide scavenging between the first two precipitations. The samples mounted for radiation measurements were in the form of AgCl deposits of 10 mg·cm^{-2} superficial density.

Radiochemical purity of the separated Ag^{115} (except for contamination with other silver fission products) was demonstrated by the constancy of the silver specific activity upon further chemical processing, and by the failure to observe decay periods and radiations from the separated silver samples other than those arising from silver isotopes and their decay products.

The decay of the gross beta activity of a silver sample separated from a target following a 30-min bombardment is shown in Fig. 1. The major component (close to 90% of the total intensity) of the beta activity of the source a few minutes after the end of bombardment is seen to exhibit a half-life of 20.0±0.5 min. In various experiments, in which the intensity of beta and gamma radiations in selected energy intervals was measured, major components with half-lives of 20.0±1.0 min were observed.

2.2. Single-Crystal Gamma-Scintillation Spectroscopy

Single-crystal gamma-scintillation spectra of the radiations from Ag^{115} were measured with NaI(Tl) detectors of 3×3 in. and 8×8 in. dimensions (from Harshaw Chemical Company, Cleveland, Ohio). The crystals were viewed by EMI 9531B or Dumont 6363 photomultipliers, of which anode signals were amplified

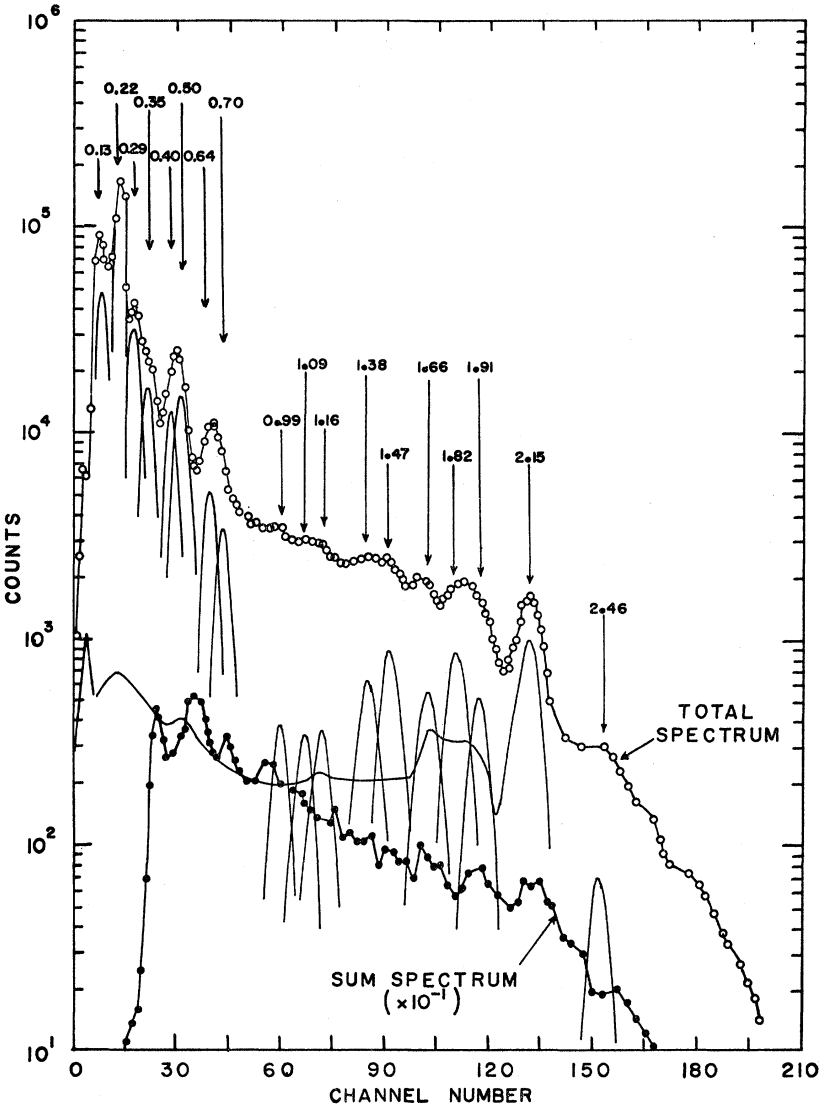

FIG. 2. Single-crystal NaI(Tl) gamma-scintillation spectrum of Ag^{115}, shown resolved into components from two-photon summing and individual gamma radiation.

either by Cosmic Radiation Laboratories model 801 amplifiers or by Franklin model 359H-358 amplifiers. Amplifier output signals were analyzed by a Technical Measurements Corporation 256-channel pulse-height analyzer or by a Radiation Instrument Development Laboratory model 34-12 pulse-height analyzer.

A single-crystal gamma-scintillation spectrum typical of those obtained a few minutes from the end of bombardment is shown as the curve labeled "total spectrum" in Fig. 2. The source, prepared as described above, was placed 3 cm from and midway between two identical 3-×3-in. NaI(Tl) detectors, with one of which the spectrum was measured. The second detector was present for purposes described below. The detectors were coaxial with the source and with each other and were shielded by beta absorbers of 1.1 $g \cdot cm^{-2}$ of Lucite. The source was mounted in a 2-cm-diam tapered aperture in a 1.3-cm lead absorber, both faces of which were covered with 0.05-cm-thick cadmium and 0.012-cm-thick copper to attenuate fluorescence radiation. The lead absorber was used to reduce the frequency of those events in which photons scattered from one crystal to the other.

The energies of the 0.22- and 2.15-MeV gamma rays (of which the full-energy peaks are prominent in the spectrum) were established in a separate experiment in which gamma radiations from sources of Ag^{115}, Mn^{54}, and Co^{60} were measured simultaneously. The energy of the sum peak from Co^{60}, which peak appeared in the spectrum and was used as an energy calibration point, was taken as 2.55 MeV.[9] The energies of the 0.22- and 2.15-MeV gamma rays were subsequently

[9] J. Kantele and R. W. Fink, Nucl. Instr. Methods **13**, 141 (1961).

TABLE I. Gamma-ray intensities.

Gamma-ray energy (MeV) (indicated range is that observed in the several analyses)	Intensity from individual analyses I (3×3 in.)	II (3×3 in.)	III (3×3 in.)	IV (8×8 in.)	Values adopted for decay scheme of Fig. 10 Gamma-ray energy (MeV)	Intensity
0.12–0.15	10	12	24	5	0.105+0.138+0.172	23
0.22±0.01	100	100	100	100	0.224+0.243	100
0.29–0.30	26	28	26	38	0.277	26
0.35–0.38	15	16	15	23	0.362+0.378	22
0.44–0.49	35	37	15	22	0.415+0.445	16
0.49–0.54	14	18	19	22	0.467	20
0.61–0.64	30	33	8	13	0.617+0.639	8
0.69–0.70	12	...	6	18	0.722	3
0.75–0.82	4	13	...	18	0.860	3
0.95–0.99	4	4	0.7	9	1.038	4
1.09–1.15	4	5	0.8	8	1.084	4
1.16–1.20	4	...	0.8	11		
1.38–1.39	5	5	16	9	1.416	5
1.47–1.50	10	10	23	9	1.483	23
1.66–1.69	11	12	16	4	1.655	16
1.80–1.83	12	14	24	10	1.760+1.861	9
1.89–1.94	18	20	15	12	1.898+2.033	20
2.15±0.05	28	30	31	19	2.122+2.138	28
2.26–2.54	3	6	2	3	2.276+2.500	4

used to provide energy calibration in other gamma-spectrum measurements to be described.

Single-crystal spectra such as that in Fig. 2 were analyzed in terms of contributions (i) from individual gamma rays, (ii) from summing events in which two gamma rays from the source interacted with the detector within the resolving time of the spectrometer system (higher order summing events are much less probable), and (iii) from a continuum due, for example, to bremsstrahlung from interaction of beta radiation with the beta absorber and other material nearby.

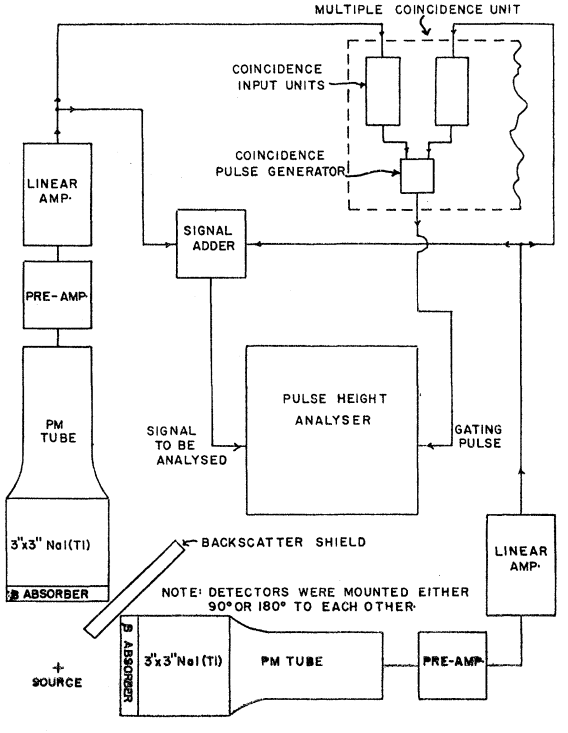

FIG. 3. Block diagram of equipment for measurement of two-photon sum spectra.

The contribution due to summing was determined by the technique due to Hoogenboom[10] which has previously been applied in the present context.[11,12] A block diagram of the equipment employed is shown in Fig. 3. The signals from the two 3-×3-in. detectors, previously matched in energy calibration by adjustment of gain, were added in a resistor network. The added signal was then analyzed whenever coincident events in each of the two detectors were registered by a Cosmic Radiation Laboratories model 801 fast-slow coincidence circuit. The sum spectrum so obtained is shown in Fig. 2. The intensity was not measured absolutely.

The shape of the continuous contribution to NaI(Tl) scintillation spectra due to bremsstrahlung was approximated with sources of beta emitters over a range of end-point energies.

The shapes of the contributions to the spectrum from monoenergetic gamma radiations of a range of energies were determined by techniques which are now common.[11,13] Spectra were measured for emitters of only one energy of gamma radiation; also emitters of two gamma rays in cascade were employed when a simple γ-γ coincidence experiment (also employing the

[10] A. M. Hoogenboom, Nucl. Instr. Methods 3, 57 (1958).
[11] N. R. Johnson, E. Eichler, G. D. O'Kelley, J. W. Chase, and J. T. Wasson, Phys. Rev. 122, 1546 (1961).
[12] G. B. Vingiani and S. Monaro, Nucl. Instr. Methods 14, 138 (1961).
[13] M. A. Wallgren, TID-11807, February 1961 (unpublished).

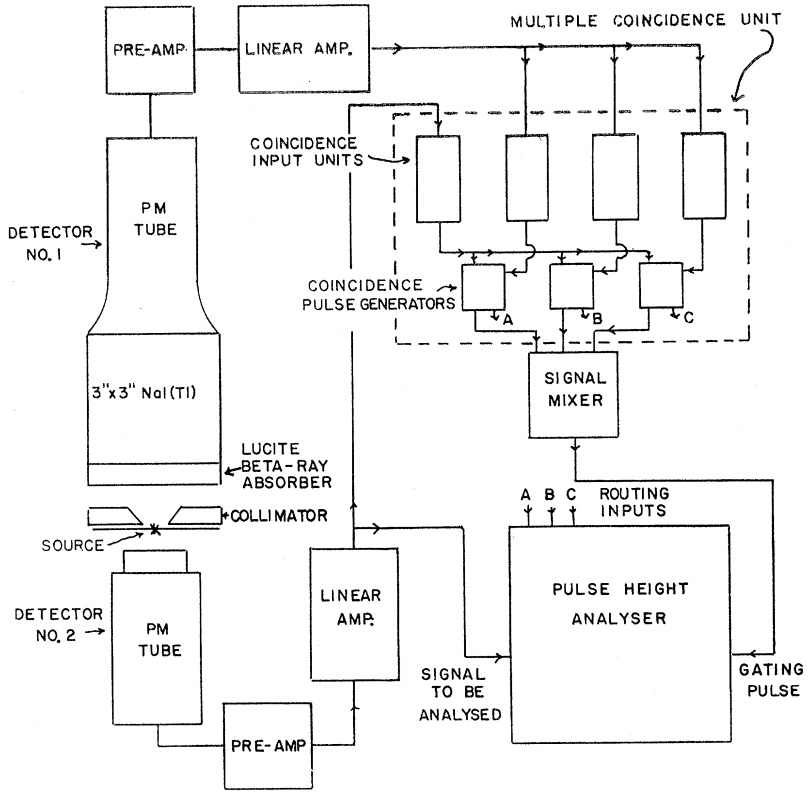

FIG. 4. Block diagram of equipment for coincidence scintillation spectrometry.

second 3-×3-in. detector) allowed the contribution from one of the radiations alone to be measured.

Figure 2 shows analysis of the Ag^{115} total spectrum into components from eighteen different monoenergetic gamma radiations plus the contribution from the sum spectrum. Only the full energy peaks of the individual pulse-amplitude distributions are shown for clarity except in the case of the 2.15-MeV gamma-ray distribution. Since the spectra obtained with the 8×8-in. NaI(Tl) detector indicated the absence of gamma radiations of energy greater than 2.5 MeV (to which this detector would have been more sensitive than—say—a 3-×3-in. detector), the sum-spectrum was normalized to the total spectrum at energies above 2.5 MeV in this analysis.

Analysis, under the alternative (and perhaps less realistic) assumption that a substantial contribution to the total spectrum arose from bremsstrahlung, produced line energies and relative intensities which did not differ substantially from those arising from the foregoing analysis except at low energies. Analysis of spectra measured at 15, 37, and 86 min after the end of bombardment yielded similar line energies and line intensities which decayed with half-lives close to 20 min; thus, the radiations are believed to follow decay of 20-min Ag^{115}.

Table I compares the results of four sets of analyses performed at different times on different data derived from different detectors. The results from the 8-×8-in. detector are considered less valuable than those from the 3-×3-in. detectors owing to increased experimental difficulties. Their main value lies in the demonstration that the spectrum does not contain gamma lines in appreciable intensity above an energy of 2.5 MeV.

The differences between the first three sets of data presumably reflect the complexity of the spectrum and of the analysis procedure. For comparison, also in Table I are presented the corresponding energies and intensities adopted in construction of the decay scheme shown in Fig. 10. It is not believed that the energy and intensity adjustments required by the construction of this scheme are beyond the range allowed by the uncertainties in the experimental data. The intensities shown in the table are all relative to that of the 0.22-MeV gamma radiation.

2.3. Gamma-Gamma Coincidence Spectroscopy

The uncertainty in the energies of some of the gamma radiations listed in Table I (and indeed the uncertainty of their very existence in some cases) was reduced by further experiments. Studies of cascade relationships between gamma transitions via gamma-gamma coincidence spectroscopy yielded spectra which were simpler, and from which certain energies could be determined more reliably than from single-crystal spectra.

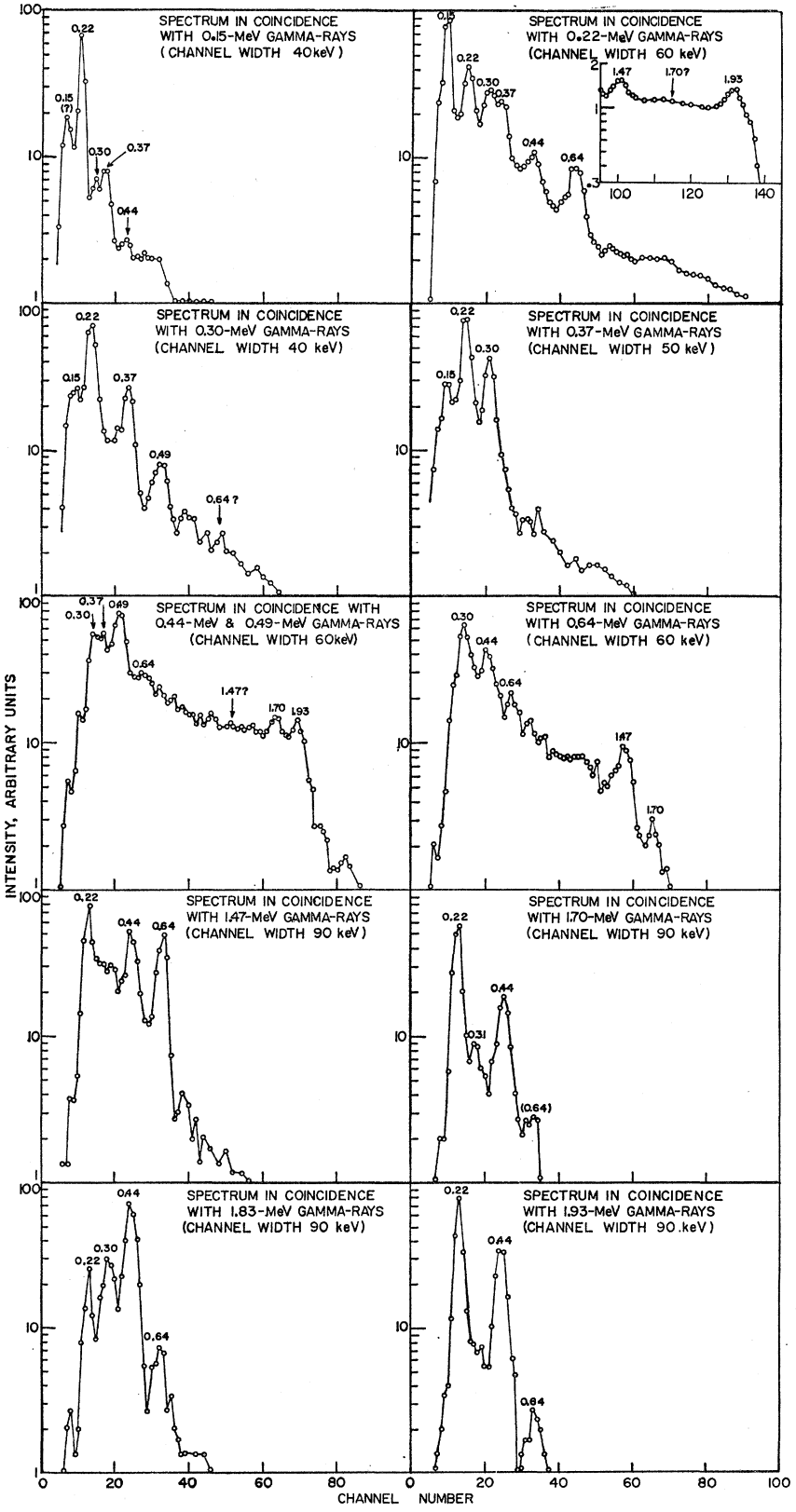

FIG. 5. Gamma-gamma scintillation coincidence spectra from Ag^{115} decay for a range of selected gamma energies.

The techniques used in these experiments were entirely conventional. A block diagram of the equipment is shown in Fig. 4 by which both γ-γ and β-γ coincidence measurements were made. In the former case, two 3-$\times$3-in. NaI(Tl) detectors, collinear with the source, plus a collimating shield and absorbers were used as described earlier. Amplification of the detector signals with amplifiers with double delay line pulse shaping allowed coincidence timing to be made at the signal return through zero voltage, via a coincidence control circuit (Cosmic Radiation Laboratories model 801 or 901). A requirement was imposed that events occur in both detectors within a short resolving time (typically 0.2 μsec), and when this was satisfied, an additional requirement was imposed that the event in one detector should fall in a specified energy interval. Satisfaction of both requirements resulted in triggering of the analysis circuitry connected to the output of the second detector, and the measurement of the spectrum of radiation in coincidence with that of the selected energy.

The selected energy interval was usually set to embrace the full-energy peak from a gamma ray of interest. The equipment employed for certain of the experiments allowed three such experiments to be performed simultaneously, with the spectra in coincidence with radiation of three different selected energy intervals being routed to and stored in different regions of the analyzer memory (as indicated in Fig. 4).

The results were corrected for effects from several sources of error. (i) The efficiency with which coincident events were detected was optimum only over a certain range of detector pulse-amplitude ratios. This range was made as large as possible by adjustment of circuit resolving times. However, the results of experiments with different amplifier gain settings were combined when a very large range of pulse-amplitude ratios were to be examined. This reduced the possibility that coincidences between very high-energy and very low-energy events, for example, escaped detection.

(ii) Chance coincidences, in which detector pulses not correlated in time satisfied the coincidence requirements, were measured in an experiment in which the coincidence detection efficiency for prompt events was reduced to zero via introduction of a differential delay between the two amplifier outputs. The spectrum measured under these circumstances was subtracted from that measured under normal timing conditions. Detector counting rates were adjusted, however, so that such random events were no more than a few percent of the total coincidence events measured.

(iii) Owing to the complexity of the single-crystal spectrum, full-energy interactions from gamma rays nearby in energy to the one of interest and Compton escape events from higher energy gamma rays will result in detector output pulses satisfying the pulse amplitude selection requirements. The contributions of such interfering effects to a spectrum measured in coincidence with events of a full-energy peak in the spectrum of Fig. 2, for example, may often be estimated via a second experiment in which the energy selection interval is moved to a somewhat higher energy. The spectrum measured under these conditions may then be compared with the result of the first experiment, under the assumption that the background under a full-energy peak in a scintillation spectrum does not, to a rough approximation, vary sharply in intensity with energy.

The results from a series of such experiments are presented in Fig. 5. This shows the spectra observed to be in coincidence with selected pulse-amplitude intervals in the output of the second detector, corresponding to 10 gamma-ray energies of interest. In view once more of the complexity of the single-crystal spectrum and of the corrections to be applied, no attempt was made to determine quantitative gamma intensities from these spectra.

Instead only approximate relative intensities were noted; these are described in Table II as strong, medium, or weak, and compared with the predictions of the proposed decay scheme of Fig. 10. The predictions are presented in the form of relative gamma intensities expected in spectra measured in coincidence with selected gamma rays of particular energies, the intensities being normalized in each case to that of the most intense gamma ray in the spectrum. It is seen that the agreement between observation and prediction is quite good within the limitations that (i) many of the observed "gamma rays" were probably doublets or triplets, (ii) a reduced efficiency for detection of coincidences involving very low- or very high-energy gamma rays evidently prevented registration of some coincidences (e.g., the 0.15- and 0.22-MeV gamma rays in coincidence with selected 0.44+0.49-MeV gamma rays), and (iii) the energy selection channel failed to resolve closely spaced gamma lines.

2.4. Sum-Coincidence Spectroscopy

The elegant technique of sum-coincidence spectroscopy was first described by Hoogenboom[10] and has since been applied by others.[11,14] In this kind of experiment, a pulse-amplitude requirement is imposed on the output of the signal adder in the equipment shown in Fig. 3. When the requirement is satisfied, the pulse-height analysis circuit, now connected not to the adder output, but to the output of either of the two detectors, is triggered. The spectrum measured will then contain contributions from all two-photon cascades whose total energy corresponds to the sum-pulse amplitude selected.

The results of such an experiment are often difficult to interpret, since contributions to the spectrum can arise from other events, for example, sums involving

[14] Gy. Màthé, D. Berényi, and T. Scharbert, Nucl. Instr. Methods 14, 209 (1961).

TABLE II. Gamma-gamma coincidence intensities (expected from proposed decay scheme and those observed).

	Gamma energy selected (MeV)	Energy of gamma-ray in coincident spectrum (MeV)																					
		"0.15"			"0.22"		"0.30"	"0.37"	"0.44+0.49"			"0.64"		"1.47"	"1.70"	"1.83"		"1.93"					
		0.105	0.138	0.172	0.224	0.243	0.277	0.362	0.415	0.445	0.467	0.617	0.639	1.483	1.655	1.760	1.861	1.898	2.033				
Decay scheme	0.105		5	1	5			6				1		1	5				1				
	0.138	5		1	100		68			3				30	2	11	8		1				
	0.172	1	1		9	9		1		1	12			10			3						
Observed	"0.15"		?		Strong		Weak	Medium		Weak													
Decay scheme	0.224	5	100	9		78	69		78	6		5		68	37	11	19	78	9				
	0.243			9	78							4		3	35		1		9				
Observed	"0.22"		Strong		Medium		Medium	Medium		Medium		Medium		Medium	Weak				Medium				
Decay scheme	0.277		90		90			100		8				84			23						
Observed	"0.30"		Medium		Strong			Strong		Medium													
Decay scheme	0.362	8		1			100			4				45	3	15	12		1				
Observed	"0.37"		Weak		Strong		Strong			Weak													
Decay scheme	0.415				100					4							12						
	0.445		3	1	8	1	8	4	4		1	2		44									
	0.467			16						1				7	62		2		16				
Observed	"0.44+0.49"						Weak	Weak		Medium		Weak		?	Medium	Medium			Medium				
Decay scheme	0.617	4	2		31	29		2			42												
	0.639									9				100			27						
Observed	"0.64"				Medium					Medium		Weak		Strong	Weak								
Decay scheme	1.483	1	45	14	100	6	93	50	50		8	22											
Observed	"1.47"				Strong		Weak	Weak		Medium		Strong											
Decay scheme	1.655	10	5		75	70		5			100												
Observed	"1.70"				Strong			Weak		Medium													
Decay scheme	1.760		56		56			63															
	1.861	1	44	14	100	6	93	49	50		8	21											
Observed	"1.83"				Medium		Medium			Strong		Weak											
Decay scheme	1.898				100																		
	2.033	2	1		12	11		1			16												
Observed	"1.93"				Strong					Medium		Weak											

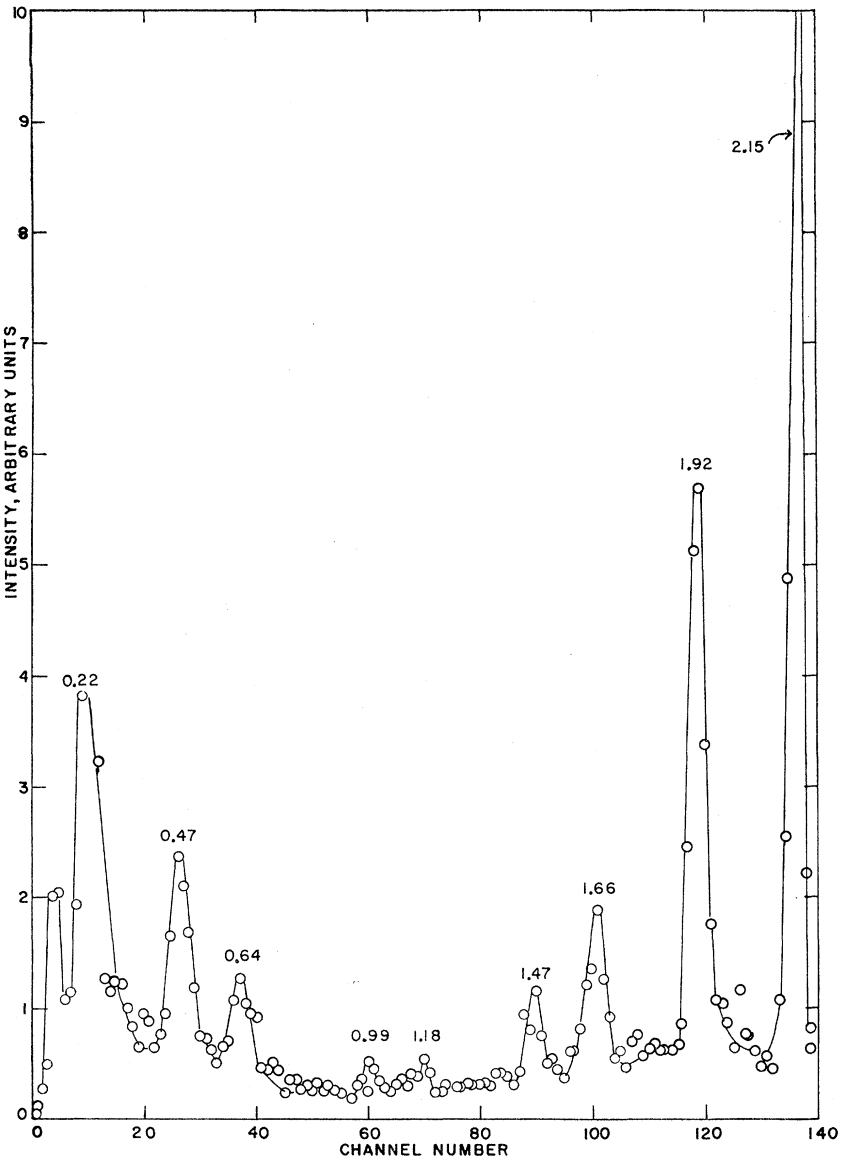

FIG. 6. Sum-coincidence (Hoogenboom) spectrum from Ag^{115} decay, with a selected sum energy of 2.15 MeV.

Compton escape events from higher energy cascades. Inspection of the sum spectrum from Ag^{115} decay in Fig. 2 shows that a prominent sum peak occurs at an energy of about 2.2 MeV, corresponding to a summed gamma energy of about 2.15 MeV plus an apparent energy increment of about 50 keV due to detector response nonlinearity.[9] There is a much lower intensity of higher energy events. Thus, it was expected that the result of an experiment in which a sum energy of 2.2 MeV was selected would be relatively unambiguous, particularly if the peaks showed the predicted[10] improved resolution.

The results of such an experiment are shown in Fig. 6. The peak at 2.15 MeV corresponds to a gamma ray of that energy impinging on one crystal alone and thus satisfying the sum requirements. The remaining eight peaks, which indeed have a smaller half-width than that characteristic of single-crystal spectra, are interpreted as arising from four two-photon cascades with a total energy near 2.15 MeV.

2.5. Beta Scintillation Spectroscopy

Beta scintillation spectra were measured with anthracene crystals of $1\frac{1}{2}$-in. diameter and of $\frac{1}{2}$-in. thickness (from Harshaw Chemical Company) coupled to Dumont 6292 photomultiplier tubes. Alternatively, Pilot "B" plastic scintillator (Pilot Chemicals, Inc.) 2 in. in diameter and $1\frac{1}{4}$ in. in thickness was used. Amplification and pulse-height analysis equipment employed has been described above. Energy calibration was accomplished by means of monoenergetic electrons from

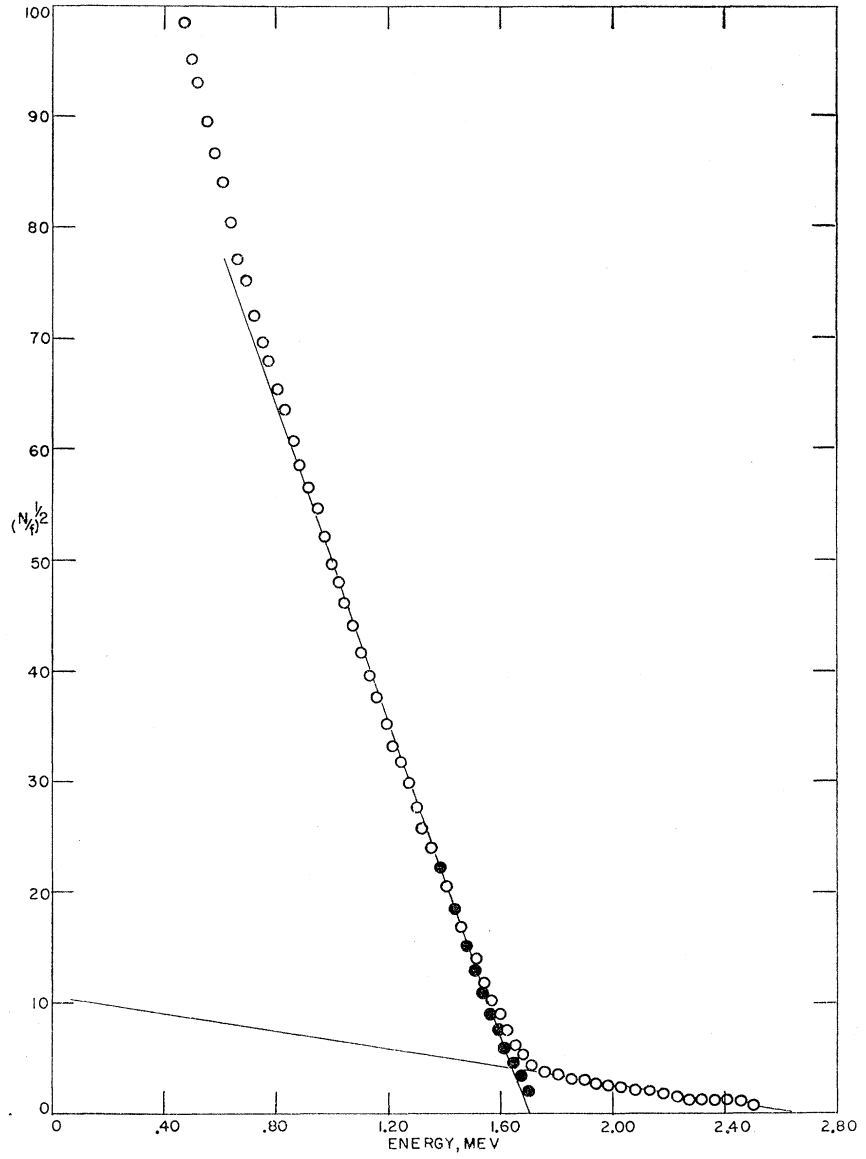

FIG. 7. Kurie plot of P^{32} beta-scintillation spectrum, measured at high counting rate. Corrections for electron backscattering from the detector have been applied.

Cs^{137} and Bi^{207}, and the end-point energies of P^{32} and Pr^{144} beta radiation.

Corrections were applied to measured beta-energy spectra for distortions introduced by backscattering of electrons from the detector before full energy deposition had occurred, by means of measurements on a series of emitters of monoenergetic electrons, and published techniques.[15–17] It was also apparent that further significant distortions of beta scintillation spectra may occur, during measurements with the equipment described above at the counting rates ordinarily employed in spectroscopy with short-lived emitters. The distortions are of the form of the introduction into the spectrum of apparent beta radiations of energies in excess of the true end-point energy. Figure 7 shows the Kurie plot of a P^{32} beta spectrum measured at a high counting rate, which illustrates this effect.

Study of the change of the relative intensity of the apparent radiations with counting rate suggested that the effect arises due to chance summation of detector output pulses arising from separate nuclear decay events. It was also found that a sufficiently large reduction of the counting-rate allowed measurement of the spectrum end-point energy, without significant interference from this source. For Ag^{115}, the end-point energy

[15] M. S. Freedman, T. B. Novey, F. T. Porter, and F. Wagner, Jr., Rev. Sci. Instr. 27, 716 (1956).
[16] H. E. Bosch and T. Urstein, University of California Radiation Laboratory Report UCRL-8924, 1959 (unpublished).
[17] G. Bertolini, F. Capellani, and A. Rota, Nucl. Instr. Methods 9, 107 (1960).

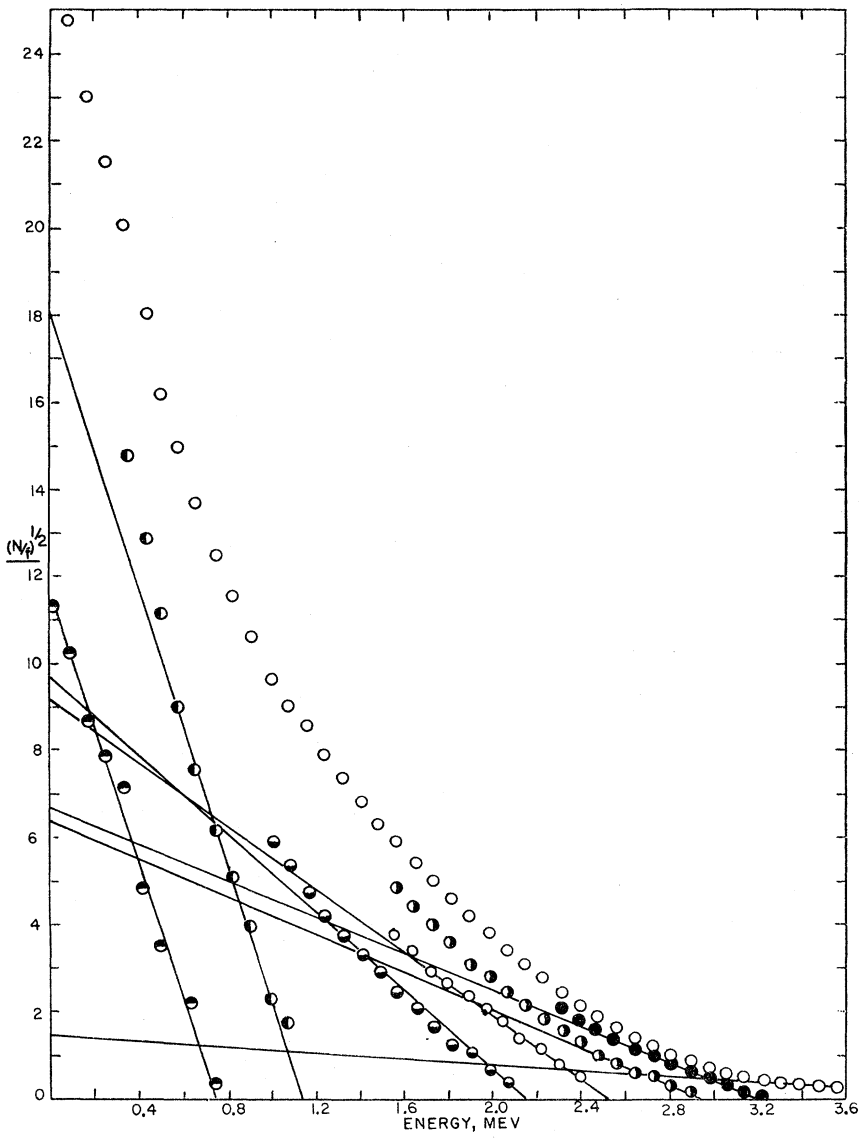

FIG. 8. Kurie plot of Ag^{115} beta-scintillation spectrum. Corrections for electron backscattering from the detector have been applied.

was thus established as 3.2 MeV, in agreement with previous measurements[7] and published nuclear mass calculations.[18]

In the case of beta-spectrum measurements, it was found necessary to separate the contribution due to Ag^{115} from that due to other silver isotopes by decay analysis. A series of multichannel pulse-height spectra was measured, over a period of time corresponding to several Ag^{115} half-lives. The data were then resolved, for each channel in the spectrum, into contributions from components of different half-lives; the intensity (extrapolated to a standard time) of the 20-min component for each channel was then plotted to obtain a multichannel beta-energy spectrum from Ag^{115} alone.

A Kurie plot from such data, corrected for electron backscattering from the detector, is shown in Fig. 8. The counting rate in this experiment was such that the summing distortion was observed. The contribution from this source to the spectrum was subtracted as though it produced a linear component in the Kurie plot. (This is seen to be roughly true for the P^{32} data in Fig. 7.) The remainder of the Kurie plot was then resolved into components of lower end-point energy. In view of the complexity of the corrections applied to the data, it is not considered that the end-point energy values of groups lower in energy than the 3.2- and 2.95-MeV groups are reliable. Certainly, no meaningful spectrum shape information is available from these data.

Coincidence measurements were also performed, in which beta spectra were measured in coincidence with

[18] P. A. Seeger, Nucl. Phys. 25, 1 (1961).

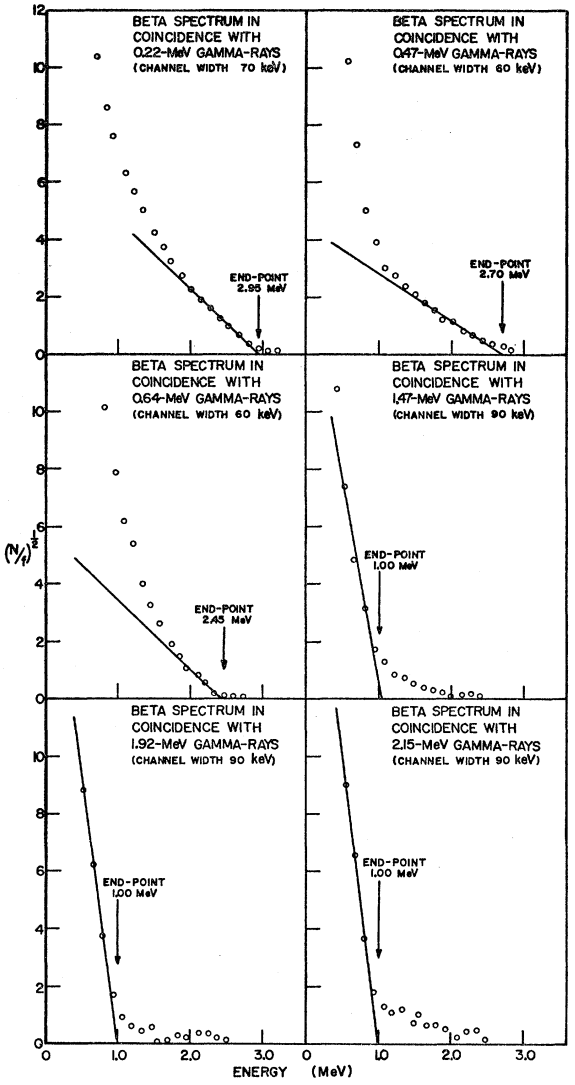

FIG. 9. Kurie plots for Ag^{115} beta-scintillation spectra observed in coincidence with gamma rays of selected energy.

events of selected energy in a 3-×3-in. NaI(Tl) gamma-ray detector. The equipment employed was that shown in the block diagram of Fig. 4. The results are shown in Fig. 9 and summarized in Table III. From these experiments, in view of the complexities in analysis, both of beta-spectrum data and of gamma-spectrum data, no attempt was made to extract more than the maximum beta energy in each case.

TABLE III. Beta-gamma coincidence experiments.

Gamma energy selected (MeV)	Channel width (keV)	Maximum beta energy (MeV)
0		3.2 ±0.1
0.22	70	2.95±0.1
0.47	60	2.7 ±0.1
0.64	60	2.45±0.1
1.47	90	1.0 ±0.1
1.92	90	1.0 ±0.1
2.15	90	1.0 ±0.1

3. DISCUSSION

The construction of the decay scheme of 20-min Ag^{115} was materially aided by the availability of data due to Gordon and Silva[19] on energy levels of Cd^{115} from a study of the $Cd^{114}(d,p)$ reaction. Energy measurements on the emitted protons led to the observation of 23 states of Cd^{115} below an excitation energy of 3.2 MeV; angular distributions led to spin and parity assignments of $\frac{1}{2}+$ for the ground state and the 0.639-MeV state, of $11/2-$ for the 0.173-MeV state (43-day Cd^{115m}), of $\frac{3}{2}+$ or $\frac{5}{2}+$ for the states at 0.224, 0.362, 0.467, 0.765, 1.084, 1.359, and 1.927 MeV, of $\frac{1}{2}-$ or $\frac{3}{2}-$ for that at 2.015 MeV, and of $\frac{5}{2}-$ or $\frac{7}{2}-$ for that at 2.122 MeV. Eight of those states fit easily into the decay scheme of 20-min Ag^{115} shown in Fig. 10, and the energies used are those of Gordon and Silva. The remaining 15 are indicated in the right-hand column of Fig. 10. Details of the Gordon-Silva work are presented elsewhere.[20]

Assignments of spin and parity $\frac{1}{2}-$ and $\frac{7}{2}+$ are expected[7,21] for ground-state and isomeric Ag^{115}, respectively, in conformity with data for Ag^{107}, Ag^{109}, and Ag^{111}. The experiments of Wahl and Bonner[6] on branching in the decay of the Ag^{115} species to 43-day Cd^{115m} $(11/2-)$ would find an easy explanation (as taken by Alexander *et al.*[7]) if the 20-min Ag^{115} had the high spin $(\frac{7}{2}+)$ corresponding to 9% net production of Cd^{115m} and the <50-sec Ag^{115} had the low spin $(\frac{1}{2}-)$ corresponding to production of <3% of Cd^{115m} from its decay. All of the decay data in the present study which relate to the spin and parity of Ag^{115} indicate the decay of a $\frac{1}{2}-$ state. Considerations of log ft values lead us to eliminate the possibility that the primary path of decay is isomeric transition of 20-min Ag^{115} of spin $\frac{7}{2}+$ to a <50-sec ground state in equilibrium at slightly lower energy with spin $\frac{1}{2}-$.

The present study provides (in Figs. 8 and 9 and Table III) evidence for appreciable β decay to the ground state of Cd^{115} and to the states at 0.224, 0.467, and 0.639 MeV. The ratio of the β intensities to the ground state and the 0.224-MeV state shown in Fig. 10 is derived from the data in Fig. 8; the absolute intensities of the decays to the four levels of Cd^{115} under consideration are derived from the gamma intensity balance of the decay scheme. Assignment of these decays to direct β transitions from 20-min Ag^{115}

[19] R. J. Silva and G. E. Gordon (private communication), 1963.
[20] R. J. Silva and G. E. Gordon, Phys. Rev. **136**, B618 (1964).
[21] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC 60-3-105.

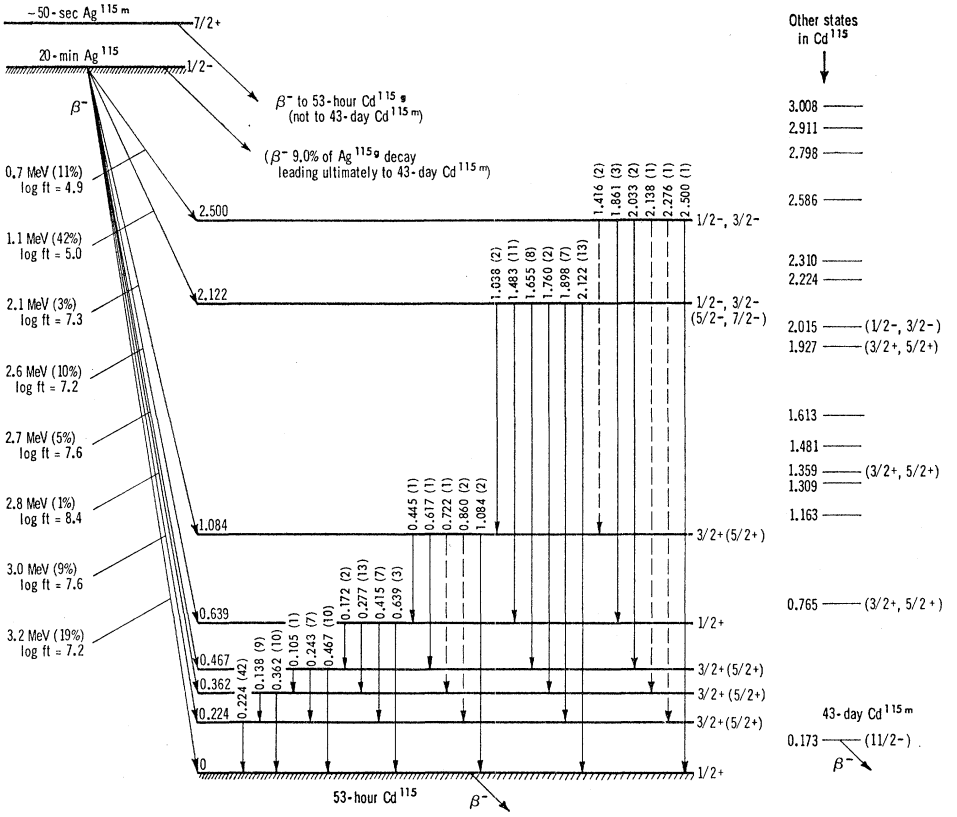

FIG. 10. Tentative decay scheme for 20-min Ag^{115}.

leads to logft values of 7.2, 7.6, 7.6, and 7.2 as expected for first-forbidden beta transitions from a state of spin $\frac{1}{2}-$ to ones of $(\frac{1}{2}+)$ or $\frac{3}{2}+$. This is in good accord with the results of a statistical analysis[22] of 295 first-forbidden transitions, giving a mean logft of 7.5 with a standard deviation of 1.5. If we postulate that these decays come from the short-lived isomer occurring in equilibrium from high-yield isomeric transition, the logft values for half-life $\sim$1 min are reduced by 1.3 to 5.9, 6.3, 6.3, and 5.9, respectively. These values are considered to be unreasonably low because only 13 of the transitions analyzed[22] have logft values this low for nuclear charge Z less than 75; the bulk of the low logft values for first-forbidden transitions are for $Z=81$, 82, or higher.

The argument against placing the short-lived Ag^{115} isomer as the ground state is supported by the observation of an intense β group (see Fig. 10) populating the 2.122-MeV level, by three sets of beta-gamma coincidence data (Table III) and by the Hoogenboom data (Fig. 6). This β group must be an allowed transition. Assuming a 20-min half-life for the β emitter the logft value for this intense β group is 5.0, whereas a 1-min half-life would give 3.7. The statistical analysis cited[22] gives for 480 allowed transitions a mean logft of 5.7 with a standard deviation of 1.1; only 10 values are reported for logft less than 4.1.

The decay scheme in Fig. 10 is based on the assumption that the 20-min Ag^{115} is the ground state and that it has spin and parity $\frac{1}{2}-$. The decay scheme uses seven excited levels[20] of Cd^{115} to account for essentially all of the body of decay data including the coincidence data of Tables II and III. Gamma transitions, of which the existence is inferred directly from the analysis of single-crystal spectra or from coincidence experiments, are shown by solid arrows. Transitions, of which the existence is presumed but not directly observed, are shown by broken lines. (The small intensities in the latter cases were chosen to be comparable with those of other transitions from the same level to states of similar spins.)

The single-crystal gamma-spectrum data of Table I are well accommodated, but with the intensities in certain cases modified to secure better agreement with the cascade intensities measured in the Hoogenboom experiment of Fig. 6. These are probably more reliable data in the case, for example, of the 1.038–1.084-MeV cascade. Also the proposed decay scheme predicts that

[22] C. E. Gleit, C.-W. Tang, and C. D. Coryell, *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC 5-5-109 to 145.

a 1.760–0.362-MeV cascade from the 2.122-MeV level to the ground state should exist; this then would have been expected to have contributed to the results of Fig. 6. Inspection of that figure indicates that the existence of such a cascade is not ruled out by the experimental data, even with an intensity in excess of that of the 1.038–1.084-MeV cascade, as required by the decay scheme.

Beta transitions are shown in Fig. 10 as populating certain states in Cd^{115}, in agreement with the data of Fig. 9 and Table III. The intensities of four of these are discussed above; the remaining intensities are derived from the intensity balance of the proposed decay scheme. It is considered that these data are accurate enough to permit classification of the transitions involved, and hence the derivation of spin and parity information. The logft estimates are shown for each β decay in Fig. 10. The value of 7.2 for the transition to the state at 0.639 MeV is consistent with the $\frac{1}{2}+$ assignment reported[20] for that state; the logft values for transitions to the states at 0.224, 0.362, 0.467, and 1.084 MeV indicate a choice of $(\frac{3}{2}+)$ for the spin and parity values from the two alternatives reported.[20] Such confirmed values are shown in Fig. 10 without parentheses; reported values not confirmed here are shown parenthetically.

The calculated logft values for the transitions to the states at 2.122 and 2.500 MeV indicate an allowed transition character in each case. Thus, given the $\frac{1}{2}-$ assignment to the Ag^{115} ground state, the assignment to these states in Cd^{115} becomes $\frac{1}{2}-$ or $\frac{3}{2}-$ in each case. No spin or parity data were previously available[20] for the 2.500-MeV state; the state at 2.122 MeV was assigned $\frac{5}{2}-$ or $\frac{7}{2}-$, values with which the present data are in conflict. It is believed that the intensity of the 1.1-MeV beta transition, from which the logft value is derived, is quite well-known from the corresponding gamma-intensity data, and that the present spin and parity assignments are therefore relatively certain.

The failure in the present work to observe indications of population of the Cd^{115} state at 0.765 MeV (viz., by its gamma de-excitation) presumably means that beta decay from Ag^{115} ground state to this state is less probable than to states nearby. This perhaps indicates a spin and parity of $\frac{5}{2}+$, rather than the alternative value[20] of $\frac{3}{2}+$. Such an assignment would lead to the expectation of some population of the 0.765-MeV state by gamma transitions possibly from the 1.084-MeV state. The total population of the 1.084-MeV state is, however, weak, so that the effects of a small fraction of the decay of this state populating the 0.765-MeV state probably would have been missed. If the assignment of $\frac{5}{2}+$ is correct, the 0.765-MeV state may be the analog of $\frac{5}{2}+$ levels which are known at similar or lower energies in Cd^{109}, Cd^{111}, and Cd^{113} [21] and possibly Cd^{117}.[20]

Corresponding conclusions regarding the spins of states at 1.359 and 1.927 MeV, for which assignments of $\frac{3}{2}+$ or $\frac{5}{2}+$ are reported,[20] must be less certain, in view of the complexity of the spectra shown earlier. The tentative assignment[20] of $\frac{1}{2}-$ or $\frac{3}{2}-$ to the state at 2.015 MeV appears unlikely in the light of the present study. Either spin value would probably lead to population of this state by allowed transition from Ag^{115} ground state in an intensity comparable to that of the transition to the 2.122-MeV state. Such a major feature of the decay scheme would probably not have escaped detection.

In short, the presently available gamma energy and intensity data are well accommodated by a decay scheme involving population only of eight states in Cd^{115} out of the twenty-three accessible. Except to the extent that gamma transitions of intensities no greater than a few percent of total Ag^{115} decay may have escaped detection, the present indications are that the states not populated at energies of say 1.613 MeV or below have spins of $\frac{5}{2}$ or higher. States at higher energies may have high-spin values, positive parity or both.

Such assignments and those shown in Fig. 10 are not inconsistent with the results of calculations by Kisslinger and Sorensen.[23] For odd-mass spherical nuclei, both quasiparticle and phonon excitations are low in energy, and together with their interactions produce a complex array of low-lying states. Thus, for Cd^{115}, the calculations predict the existence of a spin-$\frac{1}{2}$ state (other than the ground state), three spin-$\frac{3}{2}$ states, three spin-$\frac{5}{2}$ states, and also spin-$\frac{7}{2}$, -$\frac{9}{2}$, and -11/2 states all at excitations below 1 MeV of excitation. The energies predicted for states other than the 11/2− state are not in striking agreement with those postulated in the present work; however, the calculated energies do not in general show striking agreement with experimental data for other nuclei either.

There remain the problems of accommodating previous data[6] on branching ratios in Ag^{115g} and Ag^{115m} decay. The transitions, by which 11/2− Cd^{115m} is populated following 9% of the 20-min Ag^{115} decay events, were evidently not detected in the present experiments. Presumably the increase in spin from the $\frac{1}{2}$ of Ag^{115} ground state to the 11/2 of Cd^{115m} must occur in several steps; presumably also there will be extensive interconnection between the transition sequences leading to the Cd^{115} ground state and to the isomeric state, respectively. Since no evidence for any radiations recognizable as belonging to the sequence leading to Cd^{115m} was obtained, any attempt to include population of Cd^{115m} in the decay scheme of Fig. 10 must rely on speculation only. It has therefore been omitted and the decay of 20-min Ag^{115} is treated as though it ultimately populated only the Cd^{115} ground state. If some minor fraction of 20-min Ag^{115} beta decay did lead to states in Cd^{115} other than the eight

[23] L. S. Kisslinger and R. A. Sorensen, Carnegie Institute of Technology Report, Pittsburgh, 1963 (unpublished).

indicated, the calculated logft values would not be affected to a sufficiently serious extent as to change the conclusions on spin assignments described above.

The data for branching in the decay of <50-sec Ag^{115m} are more difficult to understand in terms of the proposed level scheme. Its failure to yield $11/2-$ Cd^{115m} precludes appreciable decay by isomeric transitions. If the assignment of $\frac{7}{2}+$ to this body and of high-spin values to some of the excited states of Cd^{115} is correct, the decay of the isomer would be expected to populate $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$ states in Cd^{115}, the decay of some fraction of which must populate $11/2-$ Cd^{115m}, if the above explanation of the branching in 20-min Ag^{115} decay is correct. This is in conflict with the evidence[6] that essentially none ($<3\%$) of Ag^{115} decay leads to Cd^{115m} population. We conclude that neither the problem of the branching in 20-min Ag^{115} decay, nor that of the decay of the short-lived Ag^{115} isomer have been illuminated in the present study.

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