Width of the 2.186-MeV 1^- Level in Nd^{144} †

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The resonant scattering of γ rays has been observed for the 2.186-MeV 1^- state in Nd^{144}. The electron bremsstrahlung from a Van de Graaff accelerator served as the exciting γ radiation. The scattered radiation was observed with a 40-cm^3 Ge(Li) detector. If the value $\Gamma_0/\Gamma=0.71$ is used for the branching ratio, the measured scattering yield corresponds to a partial width $\Gamma_0=(3.1\pm0.4)\times10^{-2}$ eV for the ground-state transition. The reduced $E1$ transition probability for the ground-state transition is intermediate between the $B(E1)$'s for the "spherical" nucleus Sm^{148} and the deformed nucleus Sm^{152}. A level with spin 2 and with an excitation energy of 2.074 MeV has also been excited in Nd^{144}. From the observed scattering, $\Gamma_0^2/\Gamma=(1.2\pm0.3)\times10^{-3}$ eV is obtained for this level.

I. INTRODUCTION

In previous measurements, it had been observed[1] that the reduced $E1$ transition probability for the transition from the lowest 1^- state to the ground state increased by almost one order of magnitude as one proceeded from the presumably spherical nucleus Sm^{148} to the deformed nucleus Sm^{152}. Since the nature of the 1^- states in this mass region is still poorly understood,[2] further experiments aimed at determining $E1$ transition rates are needed. The 1^- natures of the 2.186-MeV level in Nd^{144} is well established.[3] This level is populated in the decay of Pr^{144}, and resonance fluorescence studies had been carried out[4,5] using Pr^{144} as the source of 2.186-MeV γ rays. The experiments reported in Ref. 4 led to a lower limit of 1.6×10^{-14} sec for the mean lifetime of the 2.186-MeV level in Nd^{144}. Similarly, in Ref. 5, the mean lifetime of the 2.186-MeV level could be restricted to the interval $1.4\times10^{-14}<\tau<3.4\times10^{-14}$ sec only if a rather specific procedure for estimating the nonresonant elastic contribution to the counting rate was adopted. In view of the uncertainty in this estimate, the experiments of Ref. 5 had to be looked upon as providing only a lower limit of 1.4×10^{-14} sec for the mean lifetime of the 2.186-MeV level in Nd^{144}.[6] The information available with respect to this level was, therefore, not in contradiction with the suggestion, based on the Sm^{148} results,[1] that the $B(E1)$'s for the rare-earth nuclei with neutron numbers $N<90$ are smaller, by an order of magnitude or more, than the $B(E1)$ for the 0.963-MeV transition in Sm^{152}. An actual measurement of the lifetime of the 2.186-MeV level in Nd^{144} was needed, but with Pr^{144} as the source of the exciting γ radiation, it appeared to be difficult to improve upon the previous work. On the other hand, the introduction of the high-resolution Ge(Li) detectors had greatly increased the feasibility of resonance-scattering experiments utilizing bremsstrahlung. In particular, the region of atomic numbers $Z\geq35$, which could not be successfully explored as long as NaI detectors were used, had become accessible. With the availability of larger size (≥20 cm^3) Ge(Li) crystals, the limitations imposed by the small detection efficiencies of the new detectors became less serious. On the basis of resonance-scattering studies of various elements with a 40-cm^3 detector, it was concluded that the resonant scattering from the 1^- state in Nd^{144} at 2.186 MeV should be observable even if the $B(E1)$ for the ground-state transition was as small as the $B(E1)$ reported for Sm^{148}, i.e., even if the transition was retarded by a factor of 2000. The preliminary experiments had also demonstrated that a few ounces of scattering material was all that was needed; indeed, that this was all that could be used if, with the electron beam available ($\simeq20$ μA), excessive counting rates were to be avoided. This meant that, for many experiments, sufficiently large amounts of separated isotopes were available and could be used either to improve the signal-to-noise ratio and/or to reduce the complexity of the spectra. The statement made above concerning the feasibility of observing resonant scattering from the 2.186-MeV level in Nd^{144} was, in fact, already based on the assumption that separated Nd^{144} would be used. When several ounces of enriched Nd^{144} became available,[7] it was decided to carry out a resonance-scattering experiment using bremsstrahlung.

To determine the lifetime of a level, the yield of resonantly scattered photons is measured. Since the bremsstrahlung spectrum is a smooth function of the γ-ray energy, the number N_{sc} of resonantly scattered quanta is simply[8]

$$N_{sc}=N(E_R)(g\Gamma_0^2/\Gamma)G, \tag{1}$$

where $N(E_R)$ is the number of quanta per eV at the

† Work supported in part by the U. S. Atomic Energy Commission.

[1] F. R. Metzger, Phys. Rev. **137**, B1415 (1965).
[2] C. F. Perdrisat, Rev. Mod. Phys. **38**, 41 (1966).
[3] J. F. Bakken, R. Hess, and J. W. Sunier, Helv. Phys. Acta **35**, 555 (1962).
[4] P. Rice-Evans, Proc. Phys. Soc. (London) **82**, 914 (1963).
[5] J. P. Blanc, M. Lambert, and C. F. Perdrisat, Helv. Phys. Acta **36**, 820 (1963).
[6] This attitude was adopted by one of the authors of Ref. 5, C. F. Perdrisat, in his review article on $E1$ transitions (Ref. 2).
[7] Obtained from the Stable-Isotope Cross Section Research Pool of the U. S. Atomic Energy Commission.
[8] See, e.g., F. R. Metzger, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Publishing Corp., New York, 1959), Vol. 7, p. 54.

position E_R of the absorption line, emitted at 0° with respect to the electron beam into unit solid angle, Γ_0 is the partial width for the ground-state transition, Γ is the total width of the level, $g=(2I_{exc}+1)(2I_{g.s.}+1)$, and G is a factor describing the geometry, scatterer composition, etc. For a thin scatterer, i.e., if the resonant absorption is small, G does not depend on Γ_0 or Γ. For most transitions and thick scatterers, G depends rather weakly on Γ_0. In first approximation, G can thus be calculated for a given geometry without reference to Γ_0, and $N(E_R)$ is then the only additional number needed before the width, or at least $g\Gamma_0^2/\Gamma$, is obtained from the measured yield. An iteration procedure will then lead to the exact value for $g\Gamma_0^2/\Gamma$, provided Γ_0/Γ is known.

In what follows, the conditions under which N_{sc} was measured for the 2.186-MeV 1^- level in Nd^{144}, as well as for a hitherto unknown Nd^{144} level at 2.074-MeV excitation energy, will be described. Then the information obtained from the resonance-scattering experiments with respect to the spins of the two levels will be reported. This will be followed by a summary of the auxiliary measurements which were carried out to determine $N(E_R)$. Finally, the widths obtained as a results of all these experiments will be reported, and the reduced transition probabilities will be compared with those measured in other rare-earth nuclei.

II. DETERMINATION OF YIELD N_{sc}

Scattering angles of 98° and 127°, close to the minimum and the zero of the Legendre polynomial of order 2, were used, since they afforded a good check on the angular distributions and thus the spin assignments (see Sec. III). The experimental arrangement for the 98° scattering is depicted in Fig. 1. The electron beam from the Bartol Van de Graaff accelerator traversed a 35-mg/cm² gold foil and was stopped in lithium metal and carbon placed next to the gold foil. In this way, the gold foil was responsible for most of the γ radiation, i.e., the low-energy radiation was kept to a minimum. The scatterer, a right circular cylinder of neodymium oxide, 2.25 in. in diameter, and 0.625-in. long, contained in 0.0625-in.-thick Plexiglas, was placed on the beam axis at a distance of 14.4 in. from the gold target. The scattering material, a total of 82.6 g, was enriched in Nd^{144} to 97.5%. One in. of lead, placed in front of the 40-cm³ Ge(Li) detector, reduced the low-energy scattered radiation to a tolerable level. The effective center of the detector was at a distance of 6 in. from the center of the scatterer. For the 127° geometry, the target-scatterer distance was 17.3 in., the scatterer-detector distance 7 in. The two geometries thus differed by a factor of approximately 2 as far as the solid angles were concerned. In both geometries, the scatterer axis was tilted by 45° with respect to the beam direction.

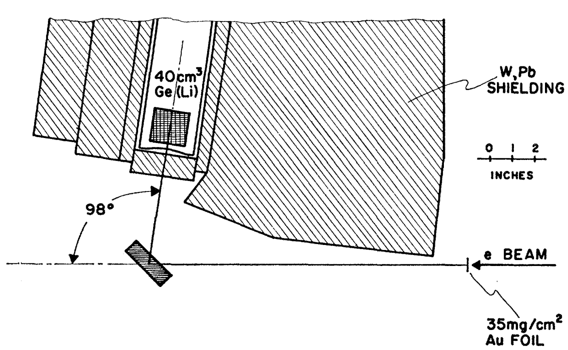

FIG. 1. The 98° scattering geometry.

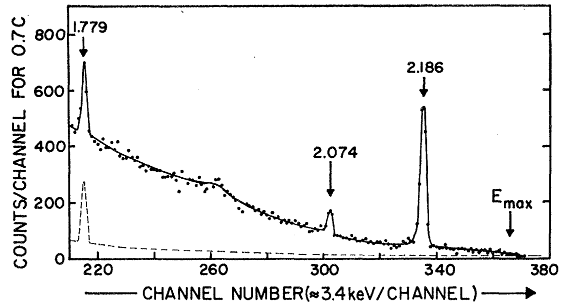

FIG. 2. Pulse-height distribution of the radiation scattered, in the geometry of Fig. 1, by 82.6 g of enriched (97.5%) $Nd_2{}^{144}O_3$. The kinetic energy of the electrons was $E_{max}=2.286$ MeV. The dashed line indicates the spectrum observed in the absence of a scatterer. The 1.779-MeV peak represents resonant scattering from the first excited state of the Si^{28} in the walls of the laboratory.

Figure 2 shows the spectrum of the scattered radiation in the energy interval from 1.76 to 2.33 MeV, measured in the geometry of Fig. 1, over a period of 16 h with an average electron current of 12 μA. The bombarding energy was 2.286 MeV. Also indicated in Fig. 2 is the spectrum obtained, for the same total bombardment, in the absence of a scatterer. The line appearing in both spectra at 1.779 MeV represents the resonant scattering from the first excited state in the Si^{28} of the building materials of the laboratory. The lines at 2.074±0.002 and 2.186±0.001 MeV are attributed to the enriched Nd_2O_3. In additional experiments, in which natural Nd_2O_3 was used as the scattering material, the two peaks were reduced by a factor of about 4. Since the two scatterers contained approximately the same amounts of Nd_2O_3 and since the natural abundance of Nd^{144} is 23.8%, this result proved that Nd^{144} was responsible for the lines at 2.074 and 2.186 MeV. Further runs at a bombarding energy of 2.174 MeV, i.e., below the threshold for the 2.186-MeV level, again resulted in the excitation of a 2.074-MeV γ ray. The absence of the strong 2.186-MeV line and the lower bombarding energy combined to improve the signal-to-noise ratio for the 2.074-MeV line. The experiment at the lower bombarding energy also eliminated the possibility that the 2.074-MeV line could have been part of a cascade originating from the 2.186-MeV level. This possibility

TABLE I. Counting rates in the 2.074- and 2.186-MeV full-energy peaks, measured at bombarding energies of 2.174 and 2.286 MeV, respectively.

Level energy in MeV	Counts per 10^5 μC 98°	127°
2.074	32.5±5	8.0±2.3
2.186	193±7	124±6

had been a rather remote one, since no indication for a 2.074-MeV line had been found in the studies[9] of the disintegration of Pr^{144}.

The observed counting rates N_{sc} for the two Nd^{144} lines are summarized in Table I. The rates given refer to excitation with bremsstrahlung having an endpoint energy 100 keV above the level energy. In comparing the counting rates for the 98° scattering with those for the 127° scattering, allowance should be made for the difference, of approximately a factor of 2, in the over-all solid angles, the solid angle for the 98° geometry being the bigger one.

It might be mentioned that the 1.489-MeV cascade transition from the 2.186-MeV 1^- level to the 0.696-MeV 2^+ level in Nd^{144} was seen in the spectrum with about the intensity expected on the basis of the known[10] branching. However, the magnitude of the background counting rate at the position of the 1.489-MeV line—approximately 50 times the background at 2.186 MeV—precluded an accurate determination of the intensity of the 1.489-MeV line.

Further examination of the spectrum indicated that considerable branching from the 2.074-MeV level to the 0.696-MeV state may take place. Because of the high background and the low intensity of the 2.074-MeV excitation, the best estimate is that $\Gamma_1/\Gamma_0 = 2\pm1$, where Γ_1 is the partial width for the 1.378-MeV transition 2.074→0.696 MeV.

III. SPINS OF 2.074- AND 2.186-MeV LEVELS

Since the even-even nucleus Nd^{144} was found to be responsible for the resonant scattering at 2.074 and 2.186 MeV, the excitation of these levels as well as their deexcitation directly to the ground state must proceed via pure multipoles. This means that for each value of the spin of the resonantly excited state, there exists just one angular distribution function $W(\theta)$, as opposed to the case of mixed transition in which a different $W(\theta)$ is expected for each value of the mixing amplitude δ. The scattering angles chosen for the Nd^{144} experiment were such that the ratios $W(98°)/W(127°)$ expected for the possible spin values of 1, 2, and 3 were drastically different. Thus, a determination of the spin could be effected even with rather poor counting statistics.

In Table II, the ratios of the counting rates at 98° and 127°, expected for different values of the spin of the excited state and for the actual geometries, are compared with the experimental ratios calculated from the numbers given in Table I. For the 2.186-MeV level, only the assignment of spin 1, which agrees with the accepted value, is compatible with the experimental result. For the 2.074-MeV level, spin 2 is strongly favored (98% confidence level).

IV. DETERMINATION OF $N(E_R)$

As long as one relies on resonance-scattering experiments, rather than self-absorption measurements, for the determination of level widths, he is limited in the attainable accuracy by the precision with which $N(E_R)$, the number of incident γ rays per unit energy interval at the resonant energy, is known for every volume element of the scatterer.

In accord with the findings of previous workers,[11] it was concluded that the most practical method of determining $N(E_R)$ made use of levels with known lifetimes. To reduce the effort involved in determining the γ-ray flux, $N(E)$ was measured for a rather specialized situation. The bombarding energy for each level was set at 100 keV above the level energy. What was measured was thus $N(E_{max}-0.1\text{ MeV})$, where E_{max} is the kinetic energy of the electrons. Scatterers deviating by not more than ±0.25 in. from the standard $2\frac{1}{4}$ in. diam were used throughout. The target-to-scatterer distance varied at most from 14 to 18 in. The Au target thickness was 35 mg/cm^2, and the same target assembly with (Li+C) beam stopper was used in all the experiments. Furthermore, in analyzing the data, it was assumed that the γ intensity was constant over the range of emission angles subtended by the scatterers.

The levels used for the determination of $N(E)$ are listed in Table III together with the relevant parameters.

For the 2.564-MeV level in Mn^{55}, a self-absorption experiment was carried out, since previous measure-

TABLE II. Comparison of the experimental ratios of the counting rates in the 98° and 127° scattering geometries with the ratios expected for different values of the spins of the excited states.

	$N_{sc}(98°)/N_{sc}(127°)$ 2.074-MeV level		2.186-MeV level	
Spin	Theor	Expt	Theor	Expt
1	1.61		1.57	
2	4.04	3.6±0.8	3.98	1.56±0.10
3	0.61		0.60	

[9] S. Raman, Nucl. Phys. **107**, 402 (1968).
[10] S. Raman, Nucl. Data, Sect. B **2**, 1 (1967).

[11] E. C. Booth, B. Chasan, and K. A. Wright, Nucl. Phys. **57**, 403 (1964).

ments[12] had determined the width only to 20% accuracy.

The results of the $N(E)$ measurements are summarized in Fig. 3. Within the experimental accuracy, $N(E_{max}-0.1\text{ MeV})$, averaged over a 4° (half-angle) cone with the electron beam direction as its axis, was found to be independent of the bombarding (electron) energy. If it is assumed that $N(E_{max}-0.1\text{ MeV})_{av}$ is indeed independent of E_{max}, a mean value

$$N(E_{max}-0.1\text{ MeV})_{av} = (9.0\pm0.6)\times10^3 \text{ photons}/(\text{eV}^{-1}\,\mu\text{C}^{-1}\,\text{sr}^{-1})$$

is obtained. Booth and co-workers[11] had found that $N(0.9\times E_{max})$ at 11° with respect to the electron beam direction was also rather constant for bombarding energies E_{max} ranging from 1.65 to 3.96 MeV.

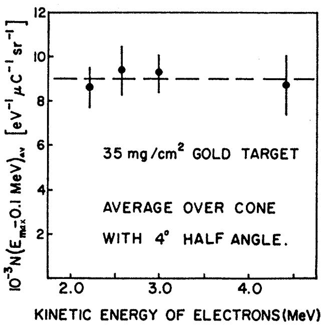

FIG. 3. Photon intensity 100 keV below the endpoint E_{max} of the bremsstrahlung spectrum, for different endpoint energies. The measured points represent averages over a 4° cone having the direction of the incident electron beam as its axis. The levels used for these measurements are listed in Table III.

TABLE III. Widths and energies of the levels used for the determination of the γ-ray flux.

Isotope	E_{level}[a] (MeV)	$g\Gamma_0^2/\Gamma$ (10^{-2} eV)	Origin of $g\Gamma_0^2/\Gamma$ value
Al^{27}	2.209	2.14±0.11	Average mean lifetime quoted in Ref. a, $\Gamma_0/\Gamma=1.00$
Mn^{55}	2.564	5.0±0.5	F. R. Metzger, unpublished self-absorption experiment, $\Gamma_0/\Gamma=1.00$
Al^{27}	2.980	7.28±0.53	Average mean lifetime quoted in Ref. a, $\Gamma_0/\Gamma=0.99$
Al^{27}	4.409	14±1	Resonant scattering of $N^{15}(p,\alpha)C^{12}$ γ rays[b]

[a] P. M. Endt and C. van der Leun, Nucl. Phys. **105**, 1 (1967).
[b] F. R. Metzger, Phys. Rev. **130**, B1464 (1965).

V. RESULTS AND DISCUSSION

When the intermediate results of the preceding sections are combined with the calculated geometrical factors G [see Eq. (1)], the following widths are obtained:

$$(\Gamma_0^2/\Gamma)_{2.186}=(2.23\pm0.26)\times10^{-2}\text{ eV},$$

$$(\Gamma_0^2/\Gamma)_{2.074}=(1.2\pm0.3)\times10^{-3}\text{ eV}.$$

The result obtained for the 2.074-MeV transition shows that, in the region of $Z=60$, widths as small as 1 meV can be measured under favorable circumstances, i.e., lifetimes as long as $\simeq10^{-12}$ sec. Of course, if the abundance and/or the branching ratio Γ_0/Γ are small, this limit will be displaced towards shorter lifetimes.

If the 1.378-MeV branch from the 2.074-MeV level to the 0.696-MeV level is assumed to be the only transition competing with the ground-state transition, the estimated branching ratio $\Gamma_1/\Gamma_0=2\pm1$ leads to $\Gamma_0/\Gamma=0.33$, and thus to

$$(\Gamma_0)_{2.074}=(3.6\pm1.5)\times10^{-3}\text{ eV},$$

and to a total width

$$\Gamma_{2.074}=(11\pm6)\times10^{-3}\text{ eV},$$

corresponding to a mean lifetime of 6×10^{-14} sec for the 2.074-MeV state in Nd^{144}. On the basis of the criteria adopted by the ORNL Nuclear Data Group,[13] the observed width Γ_0 excludes a magnetic quadrupole assignment to the 2.074-MeV transition, and leads to a 2^+ assignment for the 2.074-MeV state. The reduced $E2$ transition probability for the 2.074-MeV ground-state transition, $B(E2\downarrow)_{2.074}=116\ e^2\ F^4$, is somewhat smaller than two Weisskopf units.

With the value[10] $\Gamma_0/\Gamma=0.71$, a partial width

$$(\Gamma_0)_{2.186}=(3.1\pm0.4)\times10^{-2}\text{ eV}$$

is obtained for the 2.186-MeV $E1$ ground-state transition. The total width $\Gamma=(4.4\pm0.6)\times10^{-2}$ eV corresponds to a mean lifetime $\tau_{level}=(1.5\pm0.2)\times10^{-14}$ sec, which is in fair agreement with the lower limits established in previous experiments.[4,5]

The reduced $E1$ transition probabilities for the two

TABLE IV. Reduced $E1$ transition probabilities in Nd^{144}, Sm^{148}, and Sm^{152}. The $B(E1)$ values for the Sm isotopes were taken from Ref. 1.

Nucleus	Level energy (MeV)	Neutron number	$B(E1;\ 1^-\to0^+)$ ($10^{-3}\ e^2F^2$)	$B(E1;\ 1^-\to2^+)$ ($10^{-3}\ e^2F^2$)
Nd^{144}	2.186	84	2.8±0.4	3.8±0.5
Sm^{148}	1.464	86	0.9±0.3	2.3±0.8
Sm^{152}	0.963	90	7.9±0.8	15.4±2.0

[12] W. T. Alston, H. H. Wilson, and E. C. Booth, Nucl. Phys. **A116**, 281 (1968).

[13] See, e.g., Nucl. Data, Sect. B **1**, 1 (1966).

$E1$ transitions originating from the 2.186-MeV level of Nd^{144} are compared in Table IV with the results obtained previously for the lowest 1^- states in Sm^{148} and Sm^{152}.

The result obtained for Nd^{144} does not give a simple clue concerning the nature of the low-lying 1^- states. If, as one might naively assume, the 1^- states in Sm^{148} and Nd^{144} are members of $K=0$ negative-parity bands which exist because of a small residual deformation, then the $B(E1)$'s would be expected to become progressively smaller as one moves to smaller neutron numbers, i.e., as the residual deformation becomes smaller. The Nd^{144} results do not support such an assumption. Since no model seems[2] to explain satisfactorily the properties of the 1^- states in this region, many more $B(E1)$'s on both sides of $N=88$ should be measured. A definite trend might then become apparent and might provide a clue as to the nature of these 1^- states. The work reported in this paper has demonstrated that resonant scattering of γ rays utilizing the combination of Ge(Li) detectors and electron bremsstrahlung is a very suitable tool for this purpose.

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$E3$ Isomer in Ag^{105} †

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An $E3$ isomer has been found in Ag^{105}. The isomeric transition with half-life 7.23 ± 0.16 min is attributed to a 25.5-keV transition to the ground state. Electron-capture branching to known levels in Pd^{105} has been observed. The reduced radiative lifetimes of the five $E3$ isomers now known in odd-A silver isotopes are compared and found to be constant within a factor of 2.

I. INTRODUCTION

Most of the odd-A nuclei with neutron or proton number between 41 and 49 show $E3$ or M4 isomerism. The M4 isomerism is accounted for in the simplest version of the odd-group model by the occupation of the $p_{1/2}$ and $g_{9/2}$ shell-model states. The observation of the $E3$ isomers involving states with spin and parity $\frac{7}{2}^+$ and $\frac{1}{2}^-$ requires other explanations; in particular, the "anomalous" coupling $(g_{9/2})^n{}_{7/2^+}$, the possibility of deformed states, and the influence of coupling between particle and collective modes have been considered.

Three low-lying states with spins $\frac{1}{2}^-$, $\frac{7}{2}^+$, and $\frac{9}{2}^+$ are generally observed in the odd-A silver isotopes. The ground states of silver 113, 111, 109, 107, and 105 have been measured as $\frac{1}{2}$ while the ground-state spin of Ag^{103} has been measured as $\frac{7}{2}$. In all these isotopes, with the exception of Ag^{105}, an $E3$ isomer has been suggested. Isomeric states with nuclear spin and parity $\frac{7}{2}^+$ have been located at 70, 88, and 93 keV above the ground state in silver 111, 109, and 107 while a $\frac{1}{2}^-$ isomeric level has been located 138 keV above the ground state of Ag^{103}. It therefore appears likely that a $\frac{7}{2}^+$ isomeric state should also exist in Ag^{105} and it is probable that this isomeric level is located quite close to the ground state.

The spin of 55-min Cd^{105}, the parent of Ag^{105} has been directly measured[1] as $\frac{5}{2}$ and positive parity has been inferred. The β-decay of this parent should either directly populate the presumed $\frac{7}{2}^+$ isomeric level in Ag^{105} or feed it indirectly via other excited states in Ag^{105}. An earlier investigation[2] at Princeton of the γ radiations accompanying the decay of Cd^{105} failed to reveal any transition whose properties were consistent with the anticipated low-energy isomer. Accordingly, we commenced a search for the isomeric state by a direct chemical separation of Ag fractions from a source of isotopically separated Cd^{105}.

II. EXPERIMENTAL PROCEDURE

Cadmium isotopes were formed via (p, xn) reactions by bombarding natural Ag with 35-MeV protons from the Princeton AVF Cyclotron. After irradiation, the active portion of the target was placed in the ion source of the Princeton electromagnetic isotope separator and the cadmium radio-isotopes mass-dispersed and collected on an aluminum catcher foil. A radio-autograph of the isotope separator catcher foil is shown in Fig. 1. At this proton energy the great specificity of the Cd^{105} production is readily apparent, only very small amounts of Cd^{104} and Cd^{107} being detected.

The portion of the catcher foil at the mass-105 position was dissolved, and the Ag precipitated as AgCl. This precipitate was filtered, washed, and used for

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[1] N. S. Laulainen and M. N. McDermott, Bull. Am. Phys. Soc. **13**, 357 (1968).

[2] C. L. Starke, E. A. Phillips, and E. H. Spejewski, Nucl. Phys. (to be published).