Properties of the 319-keV Excited State of Pd^{105}†

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Using the high peripheral velocities of an ultracentrifuge as the means of compensating for the recoil energy losses, resonance scattering from the 319-keV level in Pd^{105} has been observed with a Rh^{105} source. From the magnitude of the scattering effect, a mean life $\tau_\gamma=(2I+1)(0.91\pm0.05)\times10^{-11}$ sec, I being the spin of the excited state, was obtained for the ground-state transition which is a mixture of $M1$ and $E2$. The angular distribution of the resonance radiation was found to be of the form $W(\theta)=1+(0.25\pm0.03)P_2(\cos\theta)$; this eliminated the value 1/2 for the spin of the excited state. Combining the measured mean life with the $B(E2)$ from Coulomb excitation, the absolute value of the mixing amplitude δ may be restricted to $|\delta|=0.14_{-0.02}^{+0.03}$. The experimentally observed angular distribution and this value of $|\delta|$ cannot be accounted for if a spin of 3/2 is assigned to the 319-keV level. Of the two remaining spin values, 5/2 and 7/2, spin 7/2 is favored by the experimental evidence.

INTRODUCTION

APPROXIMATELY 10% of the decays of 35.3-h Rh^{105} are accompanied by the emission of a gamma ray for the energy of which values ranging from 310 to 322 keV have been reported.[1] It is quite likely that this transition is identical with the 319-keV transition observed[2] in the decay of Ag^{105}. In Coulomb excitation studies of Pd^{105}, the 319-keV level was only weakly excited,[3] the predominant excitations[3,4] were to the 440-keV level and, to a lesser extent, to the 270-keV level. On the basis of the feeding of the 319-keV level in the decays of Rh^{105} and Ag^{105}, the spin assignments 5/2 or 7/2 were favored.[2] Aside from a value[3] for the reduced $E2$ transition probability for excitation, $B(E2)_{exc}=(9_{-2}^{+3})\times10^{-51}$ cm^4, nothing was known about the electromagnetic transition probabilities of the 319-keV state.

Recent improvements in the design of ultracentrifuges and in the tensile strengths of available rotor materials have brought the 319-keV transition within the range of applicability of the centrifuge method.[5] The observation of resonance fluorescence promised, in addition to the lifetime, information concerning the relative phases of the $M1$ and $E2$ matrix elements and, possibly, a clearer indication of the correct spin assignment.

EXPERIMENTAL PROCEDURES

Ruthenium powder, enriched[6] to 98.16% in Ru^{104}, was irradiated in the hydraulic facility of the Oak Ridge National Laboratory Research Reactor in a slow-neutron flux of approximately 2.5×10^{14} n/cm^2 sec for times ranging from 24 to 36 h. Upon receipt of the irradiated material, 5 to 10 mg of the powder were sealed with epoxy resin into a small aluminum centrifuge tube of $\frac{1}{16}$-in. i.d. and $\frac{3}{16}$-in. length. Approximately 32 h after removal of the Ru powder from the reactor, the 4.5-h activity had decayed to a tolerable level and the experiments with the ultracentrifuge could commence. The source was placed into one of the tips of a star-shaped titanium alloy[7] rotor which was coupled to an air-driven 0.5-in.-diam turbine by means of a 0.071-in.-diam piano-wire shaft. The counting equipment was gated to accept counts only when the direction of emission of the gamma rays striking the scatterer subtended an angle of less than ±30 deg with the tangent to the path of the source. The gate originated from two photomultiplier tubes which received light signals from a mirror attached to the drive shaft. The palladium scatterer measured $2\frac{1}{4}$ in.$\times1\frac{1}{2}$ in.$\times\frac{3}{16}$ in.; a silver comparison scatterer was adjusted in thickness to give rise to the same nonresonant elastic scattering. The geometries used were similar to those described previously,[8] the main modification being in the shape and material of the rotor. Most of the counting was done with a single-channel analyzer accepting the full energy peak of the 319-keV line. With one source, the pulse-height distribution was also measured with a 400-channel analyzer.

In a first set of experiments, the resonance effect at a given scattering angle (123°) was measured for a dozen source velocities ranging from zero to 1.03×10^5 cm/sec. In a second set of experiments, the source velocity was kept at its optimum value (1.01×10^5 cm/sec), and the resonance effect for different scattering angles (105°, 125°, 144°) was determined. The first set served as a confirmation of the assumptions made in the evaluation of the centrifuge experiment and, since 123° is close to the zero of the Legendre polynomial $P_2(\cos\theta)$, also gave a reliable value for the total resonance scattering cross section. The second set served mainly to

† Supported by a grant from the National Science Foundation.
[1] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).
[2] T. Suter, P. Reyer-Suter, W. Scheuer, E. Aase, and G. Bäckström, Arkiv Fysik **20**, 431 (1962).
[3] P. H. Stelson (private communication) and reference 1.
[4] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[5] P. B. Moon, Proc. Phys. Soc. (London) **A64**, 76 (1951).
[6] Obtained from the Stable Isotopes Division of the Atomic Energy Commission.
[7] C-135AMo, manufactured by the Crucible Steel Company of America.
[8] See, e.g., B. I. Deutch and F. R. Metzger, Phys. Rev. **122**, 848 (1961).

TABLE I. Limits ($|\delta|<1$) imposed, for different values of the spin of the 319-keV state, on the $E2/M1$ mixing amplitude δ by the experimental angular distribution.

Spin	Range of δ values for $A_2/A_0=0.25\pm0.03$
3/2	$0.32<\delta<0.39$
5/2	$0.037<\delta<0.095$
7/2	$-0.111<\delta<-0.076$
	$0.46<\delta<0.52$

determine the angular distribution of the resonance radiation; when combined with a measurement of the absolute source strength it, too, led to a value for the total scattering cross section. Three different sources were used; one for the measurement of the resonance effect versus velocity curve, two for the determination of the angular distribution.

RESULTS AND DISCUSSION

Typical pulse-height distributions of the scattered radiation for a source velocity of 1.01×10^5 cm/sec and a scattering angle of 123° are shown in Fig. 1. In judging the relative intensities of the different components of the scattered radiation, it should be borne in mind that the distributions were measured with $\frac{1}{16}$ in. of Pb in front of the detector, a $1\frac{1}{2}$ in.$\times1\frac{1}{2}$ in. NaI crystal.

With the single-channel analyzer accepting the interval indicated in Fig. 1, the velocity dependence depicted in Fig. 2 was measured. The smooth curve represents the behavior of the resonance effect expected[8] for an effective temperature $\frac{1}{2}(T_{\text{source}}+T_{\text{scatterer}})=315°$K and a mean life $\tau_\gamma=0.95(2I+1)\times10^{-11}$ sec. For this particular run, the uncertainty in the geometry

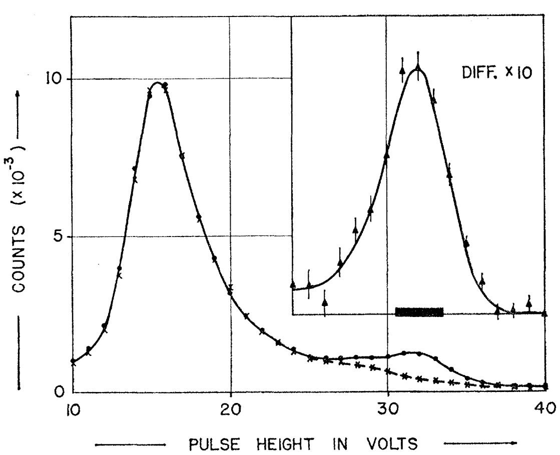

FIG. 1. Pulse-height distribution of the scattered radiation in the 123° geometry. The full circles refer to the Pd scatterer, the crosses to the Ag scatterer. The shape of the curve drawn through the difference points plotted in the insert is that of the pulse-height distribution of the direct 319-keV radiation. The position of the window accepted by the single-channel analyzer is indicated in the insert.

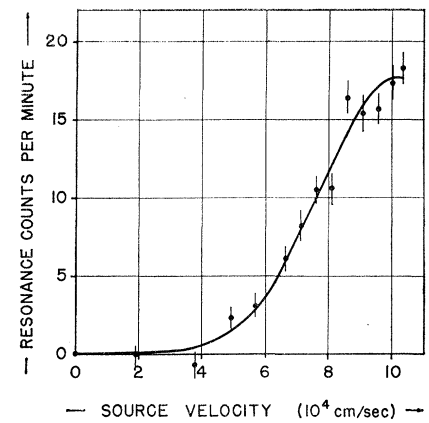

FIG. 2. Comparison of the experimental resonance scattering points (with their statistical uncertainties) with the scattering expected for $\tau_\gamma=0.95(2I+1)\times10^{-11}$ sec.

($\sim$10%) was several times the statistical uncertainty. Combining the results of all three sources, a mean life $\tau_\gamma=(0.91\pm0.05)(2I+1)\times10^{-11}$ sec was arrived at.

From the angular distribution measurements a value $A_2/A_0=0.25\pm0.03$ was obtained for the ratio of the coefficients of the first two even Legendre polynomials. In quoting the error of this ratio, only the statistical uncertainty of the counting was considered since the three geometries were very similar and only relative values of solid angles, gate lengths, etc., entered into the evaluation. This is in contrast to the determination of the mean life where the error is mainly determined by the uncertainties in the evaluation of the absolute geometry.

On the one hand, the experimental ratio A_2/A_0 restricts the possible values of the $E2/M1$ mixing amplitude δ, this restriction depending on the spin value assumed for the 319-keV state. On the other hand, a comparison of the $E2$ transition probability[3] with the total gamma-transition probability will provide limits for the absolute value of δ. In the case of the 319-keV transition in Pd^{105}, these limits are $0.12<|\delta|<0.17$. In contrast to the information from the angular distribution, these limits for $|\delta|$ do not depend on the value of the spin, since the statistical factor $(2I+1)$ appears in both the Coulomb excitation and the resonance fluorescence cross sections in the same way. If the δ intervals which are allowed by the A_2/A_0 ratio for different spin values do not overlap, a comparison with the range of $|\delta|$ values from the transition probabilities will lead to a determination of the spin of the excited state.

In Table I the ranges of δ values, allowed by the experimental A_2/A_0 ratio, are listed for the different possible spin assignments. Values of $|\delta|\geq1$ were not considered since they lie far outside the interval $0.12>|\delta|<0.17$.

It is noted that none of the ranges of Table I overlaps with the $|\delta|$ interval. However, a small increase of the

rather large errors of the $B(E2)$ value is sufficient to bring the first interval listed in Table I for spin 7/2 to overlap with the $|\delta|$ interval. To achieve overlap with the range of δ values expected for spin 3/2, on the other hand, a highly improbable increase in the error of the $B(E2)$ value would be needed. Spin 3/2 is, therefore, excluded. Spin 5/2 cannot be excluded with certainty, but the probability of the correct spin value being 7/2 is several times that for spin 5/2.

The $M1+E2$ character of the transition and the assignment of 5/2+ to the ground state make the parity of the excited state even. In all probability, the 319-keV state in Pd^{105} is, therefore, a 7/2+ state. This means that the mean life of the ground-state transition is $\tau_\gamma=7.3\times10^{-11}$ sec. Since this lifetime falls into the range accessible to delayed coincidence techniques, it might be pointed out that, in view of the good accuracy of the resonance fluorescence measurement, a direct lifetime measurement with comparable accuracy would unambiguously determine the spin of the 319-keV state.

SUMMARY

Resonance scattering from the 319-keV state in Pd^{105} has been studied with the following results:

(1) The most probable spin value is 7/2+; spins 1/2 and 3/2 are eliminated.

(2) The $E2/M1$ mixing amplitude $(I=7/2)$ is $\delta=-0.11$.

(3) The gamma-transition probability $(I=7/2)$ is $T_\gamma=(1.37\pm0.07)\times10^{10}$ sec^{-1}.

(4) The $M1$ transition probability is approximately seventy times smaller than the single-particle estimate,[9] the $E2$ transition probability is close to the single-particle estimate,[9] using $R_0=1.2\times10^{-13}\times A^{1/3}$.

[9] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), Chap. XII.

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Nuclear Resonance Excitation Using a Diffraction Monochromator*

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Nuclear resonance scattering from the first excited states in F^{19} and Mn^{55} has been studied with the bent-diffraction-crystal monochromator. The experiment was performed by observing the scattered radiation from nuclei exposed to nearly monoenergetic x rays selected by crystal diffraction from the bremsstrahlung spectrum of an x-ray tube. Gamma rays scattered at 135° from samples of lithium fluoride and manganese placed in the diffracted beam were observed as a function of the incident photon wavelength. With the lithium fluoride sample three measurements were made under different experimental conditions. In each case pronounced resonance peaks 10 to 15% above background were observed. A least-squares analysis of the data gives 109.894±0.005 keV for the energy position of the first excited level in F^{19}. From the observed yield the width of this level was deduced to be $(5.1\pm0.7)\times10^{-7}$ eV. Measurements with a Mn^{55} scattering sample gave 125.95±0.01 keV for the position of the first excited level and $(1.1\pm0.3)\times10^{-6}$ eV for the resonance width.

I. INTRODUCTION

VARIOUS techniques have been used to excite low-lying nuclear states from their respective ground states with electromagnetic fields. The techniques which have been most important in the energy region below a few MeV can be placed into four groups: (i) "Coulomb-excitation" reactions in which the nuclear excitation results from interaction of the nucleus with the electromagnetic fields of bombarding particles,[1] (ii) resonance excitation by means of gamma radiation emitted by a radioactive source,[2,3] (iii) techniques which use a nuclear reaction to provide a Doppler-shifted source of gamma radiation for nuclear excitation,[4,5] and (iv) techniques using a portion of the continuous bremsstrahlung radiation.

The possibility of observing nuclear resonance excitation using continuous radiation from a betatron was first discussed by Schiff.[6] A review of some experiments using betatron bremsstrahlung for nuclear excitation

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[1] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).
[2] F. R. Metzger, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, New York, 1959), Vol. 7.
[3] H. Frauenfelder, *The Mössbauer Effect* (W. A. Benjamin, Inc., New York, 1962).
[4] C. P. Swann and F. R. Metzger, Phys. Rev. **108**, 982 (1957).
[5] P. B. Smith and P. M. Endt, Phys. Rev. **110** 397, 1442 (1958).
[6] L. I. Schiff, Phys. Rev. **70**, 761 (1946).