elastic scattering by Elton, Swift, and Towner.[13] Calculations of the equivalent radii R of the calcium isotopes with this model, by Perey and Schiffer,[14] show even a decrease in R from Ca^{40} to Ca^{44}. A basic assumption for such calculations is, of course, the isotopic variation of the potential itself. Exploration of isotopic variations in elastic scattering of protons or alpha particles on Ca will yield information on this point, to the extent that the effect of the separate parameters in the optical potential can be disentangled. In this regard, we tentatively suggest an approach like ours, in which one focuses attention, experimentally and theoretically, on the difference in scattering. It may be, as with our work, that some of the possible ambiguities (in our case the actual choice made for the Ca^{40} parameters) turn out to be unimportant.

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SCATTERING MEASUREMENTS ON NEUTRON RESONANCES IN Pu^{239}*

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Epithermal neutron resonance scattering measurements on Pu^{239} have recently been made, using the Livermore electron linear accelerator as a pulsed neutron source for a time-of-flight experiment. The goal of this experiment was to obtain total spin values J for as many resonances of Pu^{239} as possible, and to confirm the prediction of Bohr[1] and Wheeler[2] that the total spin and average fission width are correlated. Our method, a previously reported variation[3] of the "bright line" technique,[4] eliminates the fission neutrons and capture gamma rays which complicate the analysis of an earlier scattering experiment on Pu^{239} by Fraser and Schwartz.[5] From these measurements, we have assigned J values to 15 levels of Pu^{239} up to 75.2 eV. These include seven levels (14.3, 15.5, 32.3, 35.3, 47.6, 52.6, and 75.2 eV) not determined by Fraser and Schwartz and values for three levels (14.7, 22.2, and 44.5 eV) which are in disagreement with their reported values. In addition, we have determined values of $g\Gamma_n^2/\Gamma$ for two other resonances (50.0 and 85.6 eV),

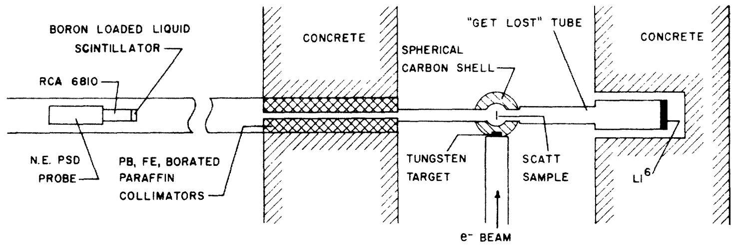

FIG. 1. The experimental arrangement. The flight path length is 17.8 m. The detector shielding is not shown. The drawing is not to scale.

but have made no total spin assignments for them.

The experimental arrangement is shown in Fig. 1. The salient feature is a spherical carbon shell, 20 cm in outer diameter with a 4.4-cm thick wall and an 0.6-cm thick hydrogenous inner liner. Bursts of fast neutrons are produced when the pulsed electron beam strikes the oil-cooled tungsten target embedded in the shell. As each neutron pulse is moderated by the carbon shell, the neutrons "forget" their point of origin and rapidly assume a spatially uniform distribution around the shell. The hydrogenous liner then serves to moderate the neutrons as quickly as possible. A Pu^{239} sample in the center of the sphere scatters neutrons to a detector at the end of the 17.8-m flight tube. Monte-Carlo calculations indicate that, for neutron energies below 10 keV, the inner surface of the shell is effectively a uniform, isotropic 4π neutron source. The width of the neutron pulse at half-maximum intensity is given by Δt (μsec) $= 3/E^{1/2}$ (eV).

The detector used in this experiment was a 5-cm-diameter by 2.5-cm-thick B^{10}-loaded liquid scintillator used with a pulse-shape discrimination circuit based on the design of Daehnick and Sherr.[6] It was shielded by 1.25 cm of lead, which in turn was shielded by about 60 cm of borated paraffin and paraffin slabs.

The collimation of the flight path was arranged so that the detector "saw" a 3.75-cm-diameter area at the center of the spherical cavity. The details of the various scattering samples used are listed in Table I. The plutonium samples were metallic foils 4.38 cm in diameter. Each was sandwiched between two 0.000 75-cm aluminum foils to prevent oxidation of the plutonium. Sample 4 was a carbon disc sandwiched in aluminum foil used to measure the flux spectrum incident on the scattering samples. An 0.000 63-cm gold foil was included in each sandwich, and the 60.3-eV gold resonance was used to normalize the measurements. Sample 5, consisted of only the aluminum and gold foils, was used to measure the sample-out background. The "get lost" tube with a 2.5-cm-thick Li^6 disc at the end insures that the wall behind the sphere does not act as a direct neutron source seen by the detector.

For all measurements, the electron pulse width was 0.6 μsec, with a repetition rate of 360 pulses per sec. The data were collected on a 4096-channel analyzer, having a channel width of 0.25 μsec. Runs of about 45 hours

Table I. Composition of scattering samples.

Sample number	Sample composition[a] (%) Pu^{239}	Pu^{240}	Pu^{241}	Other	Thickness (atoms/cm^2)
1	96.94	2.90	0.14	0.02 (Pu^{242})	9.03×10^{19}
2	96.94	2.90	0.14	0.02 (Pu^{242})	3.84×10^{20}
3	93.71	5.81	0.48	···	9.50×10^{20}
4[b]	0	0	0	carbon	1.34×10^{22}
5[c]	0	0	0	0	0

[a]All samples contained 9.2×10^{19} and 3.84×10^{19} atoms/cm^2 of Al and Au, respectively.
[b]Sample 4 is a carbon sample used to measure the neutron flux spectrum.
[c]Sample 5 is a blank sample used to measure sample-out background.

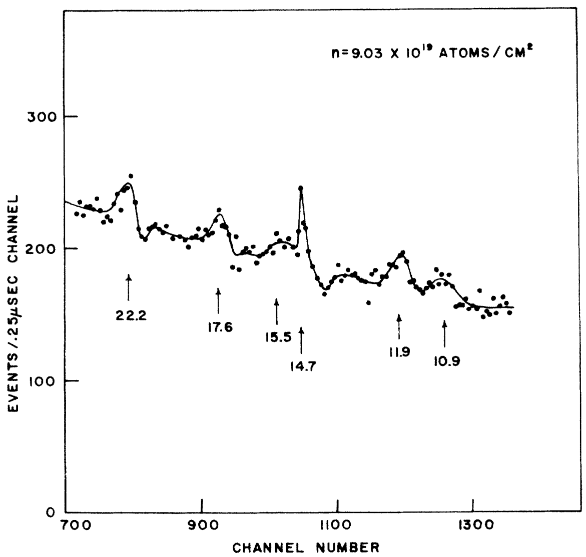

FIG. 2. A portion of the raw data from sample 1. The solid curve is included to guide the eye. The individual points represent three-channel averages.

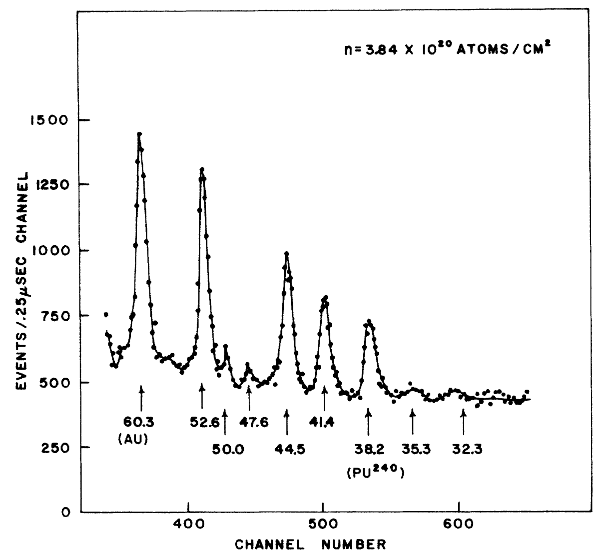

FIG. 3. A portion of the raw data from sample 2. The solid curve is included to guide the eye.

duration were made with each of the plutonium samples. Shorter neutron spectrum and sample-out background runs were taken. The raw data for portions of the two thinnest plutonium samples are shown in Figs. 2 and 3. The curves through the data are included to guide the eye. Our measurements show a significantly better signal-to-background ratio than the earlier measurements of Fraser and Schwartz,[2] this ratio being about 1 to 1 for the 44.5-eV resonance in the thinnest sample.

The Breit-Wigner formula gives the area due to scattering from an isolated resonance as $\pi\sigma_0\Gamma_n/2 = 4.088\times10^6(g\Gamma_n^{\,2}/E_\gamma\Gamma)b$ eV, where E_γ, the partial level width Γ_n, and the total level width Γ are expressed in eV, and where the statistical factor g is $(2J+1)/2(2I+1)$, with $J=I\pm\frac{1}{2}$. Since $I=\frac{1}{2}$ for Pu^{239}, the two possible g values are $\frac{1}{4}$, corresponding to $J=0$, and $\frac{3}{4}$, corresponding to $J=1$. If values of $g\Gamma_n^{\,2}/\Gamma$ are obtained from scattering areas, previously determined values for $g\Gamma_n$ and Γ can be used to find g (and hence J) for each resonance from

$$g=\frac{(g\Gamma_n)^2}{\Gamma(g\Gamma_n^{\,2}/\Gamma)}.$$

The results of our measurements are summarized in Table II. The quoted values of $g\Gamma_n^{\,2}/\Gamma$ were obtained, with two exceptions, by extrapolating the results from samples 1 and 2 to zero thickness, using the condition that $g\Gamma_n^{\,2}/\Gamma$ becomes independent of sample thickness for samples which are thin enough. By this means, effects of multiple scattering and resonance self-protection were removed from the measured values. Those effects were 10% or less of the values measured for sample 1. The quoted value of $g\Gamma_n^{\,2}/\Gamma$ for the 14.7-eV resonance is that measured for sample 1, while the value quoted for the 47.6-eV resonance is that measured for sample 2. The quoted uncertainties in the values of $g\Gamma_n^{\,2}/\Gamma$ are the estimated uncertainties in measuring the scattering areas for sample 1. We estimate the uncertainties in normalization of the various runs to be 5% or less.

The g values listed in Table II were obtained from Eq. (1) by using our measured values for $g\Gamma_n^{\,2}/\Gamma$ and two sets of $g\Gamma_n$ and Γ values reported by Schmidt[7] and by Blons et al.[8] Uncertainties in the values of $g\Gamma_n$ and Γ for the 50.0- and 85.6-eV resonances precluded any spin assignments for them. In addition, we have made J value assignments for four resonances (14.3, 15.5, 32.3, and 35.3 eV) where no quantitative evaluation of $g\Gamma_n^{\,2}/\Gamma$ was made. The reasons for these assignments are briefly outlined below.

In the interval between 13.3 and 16.5 eV, there are three resonances (14.3, 14.7, and 15.5 eV). From reported resonance parameter,[7,8] it is apparent that the 15.5-eV resonance

Table II. Measured $g\Gamma_n^2/\Gamma$ values and spin assignments.

E_r (eV)	$g\Gamma_n^2/\Gamma$ [a] (mV)	g [b]	g [c]	Assigned g	Assigned J
7.9	0.0067 ± 0.0019	0.79	0.63	$\frac{3}{4}$	1
10.9	0.0120 ± 0.0024	0.86	0.84	$\frac{3}{4}$	1
11.9	0.0160 ± 0.0031	0.63	0.56	$\frac{3}{4}$	1
14.3	<0.0045 [d]	...	...	$\frac{3}{4}$	1
14.7	0.0408 ± 0.0084	0.86	0.70	$\frac{3}{4}$	1
15.5	...	...	...	$\frac{1}{4}$	0
17.6	0.0300 ± 0.0066	0.55	0.82	$\frac{3}{4}$	1
22.2	0.0510 ± 0.0135	0.49	1.00	$\frac{3}{4}$	1
32.3	...	...	...	$\frac{1}{4}$	0
35.3	...	...	...	$\frac{3}{4}$	1
41.4	0.352 ± 0.034	0.77	0.52	$\frac{3}{4}$	1
44.5	0.598 ± 0.043	0.74	0.72	$\frac{3}{4}$	1
47.6	0.043 ± 0.014	0.12	0.16	$\frac{1}{4}$	0
50.0	0.073 ± 0.015	...	...	...	...
52.6	1.48 ± 0.096	0.67	0.78	$\frac{3}{4}$	1
75.2	2.51 ± 0.25	0.52	0.68	$\frac{3}{4}$	1
85.6	1.11 ± 0.29	...	...	...	...

[a] Quoted uncertainties are estimates of uncertainties in measuring scattering areas only.
[b] g determined using values of $g\Gamma_n$ and Γ from reference 7.
[c] g determined using values of $g\Gamma_n$ and Γ from reference 8.
[d] We could have seen some indication of the 14.3-eV resonance had $g\Gamma_n^2$ been 0.0045 mV or larger.

makes a negligible contribution to the scattering area in this interval for any choice of spin assignments to the three resonances. Also, it is easily seen that the scattering area of the 14.3-eV resonance will be about 25% that of the 14.7-eV resonance only if the total spins are 0 and 1, respectively. For any other combination of spins, the relative contribution of the 14.3-eV resonance will be less than 10%. Our experiment would detect a 10% contribution, but we observed no measureable 14.3-eV resonance scattering. Hence, we assigned all the scattering area in the interval between 13.3 and 16.5 eV to the 14.7-eV resonance, and deduced for it the total spin $J=1$. The above argument then also implies $J=1$ for the 14.3-eV resonance. On the basis of our scattering measurements, we cannot assign a total spin to the 15.5-eV resonance. However, we obtain a good fit to the recently published Pu^{239} fission cross-section measurements at Saclay,[9] using the multilevel formula of Reich and Moore,[10] only if $J=0$ for the 15.5-eV resonance when $J=1$ for the 14.3 and 14.7-eV resonances.

As can be seen from Fig. 3, the scattering areas of the resonances at 32.3 and 35.3 eV are very small, so that a small uncertainty in the position of the base line in this region causes large uncertainties in the two scattering areas. Therefore, we have not quoted $g\Gamma_n^2/\Gamma$ values for these two resonances. However, we can determine that the ratio of the two values is unity to within 25%. The recent fission measurements at Saclay[9] yield $(g\Gamma_n\Gamma_f/\Gamma)_{32.3} \approx 7(g\Gamma_n\Gamma_f/\Gamma)_{35.3}$ and $(\Gamma_f)_{32.3} \approx 21(\Gamma_f)_{35.3}$, while reported[7,8] $g\Gamma_n$ values indicate $(g\Gamma_n)_{32.3} \approx (g\Gamma_n)_{35.3}$. From these results, it is easy to show that the ratio of the two $g\Gamma_n^2/\Gamma$ values is one only if $g_{32.3}=\frac{1}{4}$ and $g_{35.3}=\frac{3}{4}$. Any other choice of g values gives a ratio differing by a factor of three from the measured ratio. Consequently, we have assigned $J=0$ to the 32.3-eV resonance and $J=1$ to the 35.3-eV resonance.

For Pu^{239}, the Bohr-Wheeler theory predicts that $J=0$ resonances should have a larger average fission width and a more symmetric fission product mass distribution than $J=1$ resonances. In earlier work, resonances in fissionable nuclei have been divided into two groups on the bases of fission width size,[11] multilevel shape analysis,[12] and fission product mass distribution.[13] However, there was no direct evidence that these groups were correlated with the spin of the compound nucleus. Using our spin assignments and the Pu^{239} fission widths recently reported by Saclay,[9] the average fission width of the $J=0$ resonances is 403 mV, while for the $J=1$ resonances the average fission width is 41.7 mV. Thus our experiment provides direct evidence that the smaller spin is associated with the larger average fission width in accordance with the theoretical prediction for Pu^{239}.

Of our 15 spin assignments, 12 are $J=1$ and three are $J=0$. This ratio of four is consistent with the ratio of three expected from a $2J+1$ dependence for the level density.

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STATIC QUADRUPOLE MOMENT OF THE FIRST EXCITED 2^+ STATE OF ^{114}Cd†

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Recently an experimental value of the static quadrupole moment, Q_2, of the first excited (2_1^+) state of ^{114}Cd was reported by several groups of authors.[1-3] The reported values of Q_2 vary somewhat but all seem to be included in the range $Q_2 = -(0.5 \pm 0.25)$ b. This strikingly large magnitude of Q_2 made the authors of reference 1 infer that ^{114}Cd is a rotational (permanently deformed) nucleus, rather than a vibrational nucleus as has so far been believed.[4]

Indeed, $Q_2 = 0$ for a vibrational model of pure harmonic nature,[5] and this model is in contradiction with experiment. However, many known experimental data[4] (other than Q_2), such as energy levels, $B(E2)$ values, and so on, indicate that ^{114}Cd is a rather typical, though not purely harmonic, vibrational nucleus. These data are very difficult to be understood if ^{114}Cd is in fact a rotational nucleus, but are fairly satisfactorily explained by models[6,7] which assume it to be a vibrational nucleus with some anharmonicity being allowed.

The purpose of the present article is to show that it is not impossible to predict a large Q_2 value within the framework of the vibrational model. Before showing this, however, we shall list the theoretical values of Q_2 calculated by using the models so far proposed by various authors.

(i) Harmonic vibrational model[5]: This model gives $Q_2 = 0$. See above.

(ii) Shell model[8]: The dominant proton configuration will be $(g_{9/2})^{-2}$, which with[9] $e_{\text{eff}} = 0$ gives[10] $Q_2 = -0.10$ b. The magnitude is too small. Inclusion of other configurations, such as $(g_{9/2})^{-4} \times (g_{7/2})^2$, will further decrease the magnitude.