olds of rare gases in alkali metals, reported here, find a quantitative explanation in terms of elegant impurity structures. However, currently accepted theories of the edge profile offer no acceptable explanation of the observed absorption above threshold. It is worth remarking that the present case differs from the case of host core excitations in that the excited electron in our studies exists initially in a region lacking host band electrons. It is therefore possible that the correct explanation of edge profile in metals may involve a true many-body problem rather than the one-electron approximations employed in current Hartree-Fock studies of these interesting processes.

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Measurement of the g Factor for the 1.1-μsec Shape Isomeric State in ^{237}Pu

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The spin precession of the 1.1-μsec shape isomeric state in ^{237}Pu has been measured by the perturbed angular correlation method. From a measurement of the spin rotation frequency as a function of temperature of the target, the paramagnetic correction factor β has been determined to be in agreement with the theoretical value of 2.86 at room temperature for a 4^+ ionic state. The deduced value for g is $+0.14 \pm 0.02$.

Two spontaneous-fission isomeric states with half-lives of 100 nsec and 1.1 μsec, respectively, have been found in ^{237}Pu.[1-3] The long-lived state (1.1 μsec) has the higher spin,[1] and appears to lie approximately 0.30 ± 0.15 MeV above the 100-nsec isomeric state.[2] The conclusions drawn from these experiments[1,2] are that the 100-nsec isomeric state probably is the ground state in the secondary minimum whereas the 1.1-μsec isomeric state is an excited single-particle state with the γ decay to the ground state hindered because of selection rules for I and K quantum numbers.

Recently Specht *et al.*[3] measured the angular distribution of the delayed-fission fragments from the two isomers and found an anisotropy of 1.41 ± 0.14 for the (1.1 μsec) excited state and of 0.58 ± 0.16 for the (100 nsec) ground state. Two conclusions are drawn from this measurement: (i) A considerable fraction of the 1.1-μsec isomeric state decays directly through a fission channel with $K < I$ rather than decaying by γ emission to the ground state; and (ii) the 100-nsec isomeric state probably decays via a fission channel with $K = I$. The authors also suggest that a likely spin combination for the two isomers is $\frac{11}{2}$ and $\frac{5}{2}$. Such a spin combination is also suggested from relative-population cross-section measurements.[1] Furthermore, this spin combination is consistent with several theoretical calculations of the single-particle levels in the secondary minimum.[4]

This Letter reports on a measurement of the g factor for the 1.1-μsec isomeric state by a study of the time-dependent angular distribution for the delayed-fission fragments when an external magnetic field is applied perpendicular to the plane of the detectors and target.

The 1.1-μsec isomer is populated via the reaction $^{235}U(\alpha, 2n)^{237m}Pu$ with an α energy of 25 MeV. The average angular-momentum input is $(6-8)\hbar$. To minimize perturbation effects from quadrupole fields, the recoils are stopped in Pb. Because of the small cross section (~1 μb), a sandwich target consisting of alternating layers of 35 $\mu g/cm^2$ of ^{235}U and 65 $\mu g/cm^2$ of natural Pb was used. In total, forty layers of each were sputtered onto a Cu backing.[5]

Two detectors (100-μm-thick Si surface-barrier detectors) placed at 135 and 225° with respect to the beam were used. Each detector subtended an angle of ± 19°.

The time spectra of fission fragments detected in between beam bursts are shown in Fig. 1. Both the short-lived and the long-lived components appear. In both spectra clear oscillating structures are observed which are out of phase, as expected

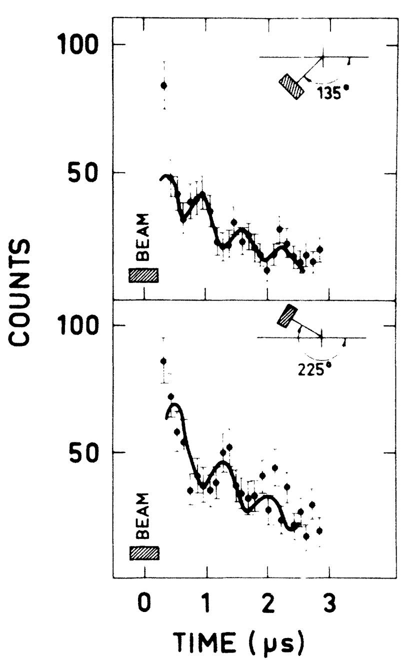

FIG. 1. Time distribution of delayed-fission fragments from the reaction $^{235}U(\alpha, 2n)^{237}Pu$. The perturbed angular correlation is seen to be out of phase for the two detectors. The external magnetic field is 2 kG.

for this detector geometry. The time-dependent angular distribution from an isomeric state with spin I and projection K on the nuclear symmetry axis can be written as

$$W_K^I(\theta, t) = \sum_\lambda A_\lambda G_\lambda P_\lambda \cos(\theta - \omega_L t), \quad \lambda = 0, 2, \ldots, 2I. \tag{1}$$

Here P_λ are the Legendre polynomials and G_λ are attenuation factors representing perturbations from extranuclear fields. For a more detailed discussion of this formula, see Ref. 3.

The A_λ terms are expected to be small for $\lambda > 2$, and for the chosen geometry the finite solid angle and the beam width tend to attenuate the contribution from the $P_{\lambda>2}$ terms more strongly than from the P_2 term, thus making the $A_{\lambda>2}$ terms negligible. By forming the difference between the counts in the two detectors and dividing by the exponential function describing the unperturbed decay, one thus obtains a simple sine function with a frequency twice the Larmor frequency ω_L:

$$f(t) = \tfrac{3}{2} A_2 G_2 \sin(2\omega_L t), \tag{2}$$

where $\omega_L = -gB\mu_N/\hbar$. In the analysis we have assumed a pure magnetic interaction and neglected possible quadrupole couplings. The effective magnetic field B acting on the nucleus has two components, the external field and an internal field due to partial polarization of the $5f$ electrons.[6] If, within the same J, the electronic level splitting $\Delta E \ll kT$, and if furthermore $B_{ext} \ll B_{5f}$, one can approximate the internal field as proportional to the external field and inversely proportional to the temperature of the target.

Under these assumptions the proportionality factor $\beta = B_{int}/B_{ext}$ has been determined by measuring the spin-rotation frequency as function of temperature of the target.[7] The results are shown in Fig. 2.

The factor β may also be estimated theoretically.[6] The various contributions to the magnetic field at the nucleus are an orbital part (B_{orb}), a core polarization part (B_{core}), the Fermi contact part ($B_{contact}$), which we shall neglect, and the applied external field. The calculation of B_{orb} and B_{core} requires the knowledge of the ionization state of the Pu ions in the Pb environment, the most likely states of which are either 3^+ or 4^+. If we assume a 3^+ ionization state, use Russell-Saunders coupling, and neglect crystalline field effects, we find $\beta = 1.36$ at room temperature. For the 4^+ ionization state we obtain $\beta = 2.86$, in

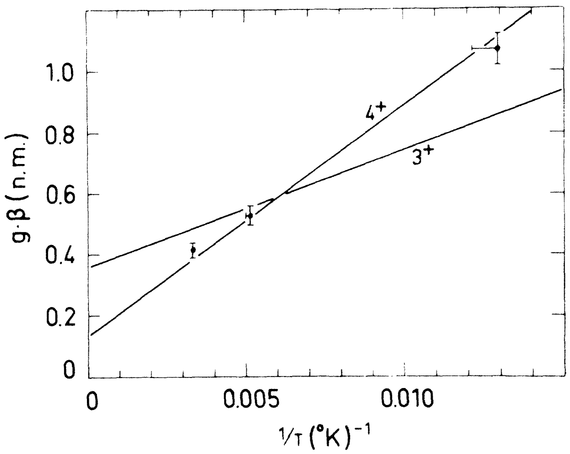

FIG. 2. Values of the product $g\beta$ measured at liquid-nitrogen, dry-ice, and room temperatures. Least-squares fits of a linear temperature dependence are shown, assuming 4^+ ($\chi^2=1.8$) and 3^+ ($\chi^2=27.3$) ionic states. The horizontal error bars represent uncertainties due to possible beam heating of the target.

close agreement with the experimental trend (see Fig. 2). We would like to point out, however, that the above discussion also neglects crystal-field effects from the lattice which in principle could be very important. If crystal fields are present, the β value may be lower. An average value $\omega_L/B_{ext}=(2.0\pm0.1)\times10^6$ sec^{-1} G^{-1} was obtained from several measurements at different magnetic fields at room temperature. Assuming $\beta=2.86$, this yields $g=+0.14\pm0.02$. The sign is determined from the phase of the oscillations and the knowledge that $W(0°)/W(90°)>1$. The anisotropy of the fission-fragment angular distribution can be extracted from the amplitude of the observed oscillations. An approximate value for this anisotropy, corrected for the finite solid angle of the detectors and for the finite length of the beam burst, is $W(0°)/W(90°)=2.3\pm0.4$. This value can only be considered as a lower limit since we have neglected perturbation caused by extranuclear fields [i.e., $G_\lambda=1$ in Eq. (1)]. Comparison of $W(0°)/W(90°)$ with Eq. (1) shows that the spin I of the isomeric state has to be equal to or larger than $\frac{7}{2}$; see Ref. 3.

The theoretical estimate for the g factor for a single-particle state described by the quantum numbers K and I moving in an axially symmetric potential can be written as

$$g=\left(1-\frac{K^2}{I(I+1)}\right)g_R+\frac{K^2}{I(I+1)}g_\Omega,\quad K\neq\tfrac{1}{2},\qquad(3)$$

with

$$\Omega g_\Omega=g_l\langle l_z\rangle+g_s\langle s_z\rangle.\qquad(4)$$

Here g_R represents the magnetic moment due to the collective flow of protons and neutrons, whereas g_Ω results from the unpaired particle.

If $K\neq\frac{1}{2}$, the isomeric state will have $K=I$ when it precesses in the magnetic field, reflecting the main component of the isomeric wave function.

Collective magnetic moments have been measured for a variety of nuclei and the experimental values for g_R lie around 0.35 ± 0.04.[8] For larger deformations, as for the secondary minimum, one could expect the value for g_R to approach its limiting value $Z/A\sim0.4$.

The Schmidt values for g_l and g_s in Eq. (4) are 0 and -3.82, respectively, for neutrons. The best estimate for g_l is -0.06 ± 0.02.[9] Because of spin polarization effects the g_s factor has to be renormalized. In the mass region $150<A<185$, one finds experimentally that $g_s=0.7g_{s\,\mathrm{free}}$.[8] For $K=I\geq\frac{7}{2}$, it is seen from Eq. (3) that the correction to g from g_R is small. This gives a positive value for g_Ω and consequently $\langle s_z\rangle$ must be negative in Eq. (4), implying that the angular momentum and the spin are antiparallel or, in terms of the Nilsson quantum numbers, $\Omega=\Lambda-\frac{1}{2}$. Earlier speculations that the long-lived isomeric state is connected to either the [615] $\frac{11}{2}^+$ or [505] $\frac{11}{2}^-$ orbit now seem ruled out. The nearest $\frac{11}{2}$ level with $\Lambda=6$ is calculated to lie approximately 10–15 MeV above the Fermi surface for ^{237}Pu, and we can therefore disregard this Ω value.

From Eqs. (3) and (4) one obtains $g(I=\frac{9}{2})=0.25\pm0.03$ and $g(I=\frac{7}{2})=0.32\pm0.03$, assuming the above values and uncertainties for g_R and g_l and assuming $g_s=0.7g_{s\,\mathrm{free}}$. For the very deformed fission isomeric state one may expect the renormalization factor to be closer to unity[8] and consequently the theoretical values for g to be even larger. Thus, there seems to be a discrepancy with the measured g factor. Also, the calculated single-particle schemes[4] do not place an $I=\frac{9}{2}$, $\Lambda=5$ state within ~3 MeV of the Fermi level for 143 neutrons.

A possible explanation of the observed low value for the g factor could be a strongly decoupled $K=\frac{1}{2}$ band where, for example, the $\frac{7}{2}$ member of the rotational band is the lowest state. Calculations of the different possibilities[10] together with measurements of the g factor for the 100-nsec isomeric state are in progress.[7]

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Off-Shell Effects in Pion-Deuteron Absorption*

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The cross section for the process $\pi^+ + d \to p + p$ is calculated using a π-N t matrix obtained from a Lagrangian formalism. The t matrix is provided with a suitable cutoff to damp the large (off-shell) momentum components and the total cross section is found to be strongly dependent on the cutoff range parameter taken, i.e., to how fast the t matrix falls off as it is taken off shell. It is argued that this is to be expected physically and that this sensitivity might provide a means of studying the π-N off-shell t matrix.

Pion absorption on nuclei provides us with two ways of obtaining information about nuclear properties. Two-nucleon absorption may hopefully provide information on nucleon-nucleon correlations, while single-nucleon absorption can provide knowledge of the single-nucleon form factor. The unique feature of these reactions, as compared with conventional nuclear reactions, is the large amount of momentum which must be found to make the reaction go. This is because the mass of the pion is converted to energy. In the case of two-nucleon absorption this momentum is obtained by having the momenta of the two final nucleons almost cancel. This still requires that the two nucleons have large relative momentum—a correspondence with short nucleon-nucleon distances. For single-nucleon absorption the recoiling residual nucleus must carry off momentum equal to that carried by the absorbing nucleon. Thus we are looking at the relative momentum distribution of the nucleon-core system.

To understand either of these processes the basic pion absorption mechanism must be understood. From the above description and from previous work (especially that of Koltun and Reitan[1]) it may be believed that the basic process involves an interaction with two nucleons. Note that the first interaction is a scattering. This is followed by a propagation (off-shell) followed by an absorption.

To learn about the basic mechanisms involved we have studied pion absorption on the deuteron. For this reaction there is no difference between two-nucleon and single-nucleon absorption.