out-of-plane correlations used by Abramson *et al.*[12] to determine wave functions in the cadmium isotopes. No calculations of these other correlations with both nuclear and Coulomb DR background or with a polarized beam have yet been performed. However, the correlation discussed here, which for 1^+ and 2^+ states is related to the spin-flip probability, it not necessarily more significant than the others in the determination of nuclear wave functions. Thus measurements of these other correlations should also be undertaken with a polarized beam, and they should not be limited to residual states of spin 1^+ and 2^+. Abramson *et al.* note, however, that a large incoherent compound-nucleus background was the largest source of error in their analysis. This problem can be avoided in the analysis of P and A measurements since the products $A\,d\sigma/d\Omega$ and $P\,d\sigma/d\Omega$ have no contributions from incoherent compound-nucleus reactions.[13]

It has previously been shown that polarized beams are useful in the study of IAR if the direct-reaction background is large.[14,4] Here we have shown that they should be important even if this background is small or nonexistent since they can be used to measure P. Further, our calculations indicate that large differences can be expected between P and A even with a large direct background provided there is sufficient exit-channel interference between waves with orbital angular momenta; it is therefore useful to measure both A and P. Thus polarized-beam studies of the particular p-γ correlation discussed here, and very likely of many other such correlations, should prove important in the study of both wave functions and reaction mechanisms for IAR.

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Mössbauer Experiments on ^{180}Hf and the Structure of the 8^- Two-Quasiparticle State*

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The magnetic moment of the 1142-keV 8^- state of ^{180}Hf was deduced from the known hyperfine splitting of the isomeric state in $(Hf_{0.1}Zr_{0.9})Fe_2$ and the hyperfine field in this compound. This field $H_{hf}=-200\pm20$ kOe was obtained from Mössbauer experiments with the 93.3-keV γ rays of ^{180}Hf. The deduced result $\mu(8^-)=+(8.6\pm1.0)\mu_N$ identifies the 8^- state as a virtually pure two-proton configuration.

Krane *et al.*[1] recently determined the parity-nonconserving forward-backward asymmetry of the 501-keV γ rays emitted by ^{180m}Hf nuclei polarized at low temperatures. Making use of the hyperfine field in the ferromagnetic cubic Laves-phase compound $(Hf_{0.1}Zr_{0.9})Fe_2$ and cooling to 0.021 K, they obtained a nuclear polarization of 72%. The corresponding magnetic hyperfine splitting of the 1142-keV state is $\Delta(8^-)=\mu(8^-)H_{hf}/I\mu_N=-(6.81\pm0.43)\times10^{-7}$ eV. We have measured the hyperfine field H_{hf} in $(Hf_{0.1}Zr_{0.9})Fe_2$ by means of Mössbauer experiments on the first excited 2^+

TABLE I. Results of the Mössbauer measurements with the 93.3-keV γ rays of ^{180}Hf. H_{ext} is the external field applied to source and absorber, d the Hf content per unit absorber area, W the full experimental linewidth, Δ the hyperfine splitting parameter as defined in the text, and H_{hf}^A the derived hyperfine field at the Hf nuclei in the $(Hf_{0.1}Zr_{0.9})Fe_2$ absorbers. The negative sign for H_{hf}^A follows from the two measurements with a $Ta_{0.002}Fe_{0.998}$ source.

Source	Absorber	H_{ext} (kOe)	d (mg/cm^2)	W (mm/sec)	Δ (mm/sec)	H_{hf}^A (kOe)
Ta metal	$HfZn_2$	0	21	2.74 ± 0.10	0	...
Ta metal	$(Hf_{0.1}Zr_{0.9})Fe_2$	0	21	2.82 ± 0.21	0.54 ± 0.07	-207 ± 29
Ta metal	$(Hf_{0.1}Zr_{0.9})Fe_2$	0	59	2.71 ± 0.14	0.52 ± 0.04	-195 ± 19
Ta metal	$(Hf_{0.1}Zr_{0.9})Fe_2$	28	27	2.37 ± 0.15	0.63 ± 0.05	-231 ± 24
Ta metal	$(Hf_{0.1}Zr_{0.9})Fe_2$	44	59	2.85 ± 0.13	0.58 ± 0.05	-213 ± 23
$Ta_{0.002}Fe_{0.998}$	$HfZn_2$	0	60	3.18 ± 0.16	2.12 ± 0.03	...
$Ta_{0.002}Fe_{0.998}$	$(Hf_{0.1}Zr_{0.9})Fe_2$	38	38	3.38 ± 0.12	1.66 ± 0.05	-161 ± 22

state of ^{180}Hf at 93.3 keV. Combining our result with the hyperfine splitting $\Delta(8^-)$, we deduce the magnetic moment of the 8^- state. Since the expected moments for the possible two-proton and two-neutron configurations differ by nearly two orders of magnitude, we can identify the 1142-keV state as a rather pure two-proton configuration, $\{\frac{7}{2}+[404],\frac{9}{2}-[514]\}_{8^-}$. The sign of the hyperfine field in $(Hf_{0.1}Zr_{0.9})Fe_2$ is found to be negative, which confirms the negative sign of the irregular $E2/M2$ mixing ratio ϵ deduced by Krane *et al.*[1] from a comparison with circular-polarization measurements.[2]

The Mössbauer measurements were performed at 4.2 K in a transmission arrangement. A superconducting solenoid provided a longitudinal external magnetic field at both the source and the absorber. The 93.3-keV γ rays were detected by either a Ge(Li) or a NaI(Tl) detector. The results of the measurements are compiled in Table I, and some of the spectra are reproduced in Fig. 1.

The intermetallic compound $Hf_{0.1}Zr_{0.9})Fe_2$ was prepared by arc melting and subsequent annealing as described in Ref. 1. The paramagnetic cubic Laves-phase compound[3] $HfZn_2$ was used as a single-line absorber. The ^{180m}Ta ($T_{1/2}=8.1$ h) used as the source was produced with high radiochemical purity by the ^{181}Ta(γ,n) reaction.

Single-line sources were obtained by exposing Ta metal foils of 200 mg/cm^2 thickness for several hours to the bremsstrahlung generated by an average current of 200 μA of 17-MeV electrons from the Argonne National Laboratory linac. With these sources and a thin single-line $HfZn_2$ absorber, an experimental line width of 1.4 times the minimum observable width[4] $W_0=2\hbar/\tau=1.95$ mm/sec was observed [Fig. 1(a) and Table I].

Spectra taken with $(Hf_{0.1}Zr_{0.9})Fe_2$ absorbers and no external field [Fig. 1(b)] show that the small hyperfine splitting in this compound cannot be resolved. The magnetic hyperfine pattern for a $2^+\to0^+$ transition consists of five lines of equal intensity and a separation $\Delta(2^+)=|g(2^+)\mu_N H_{hf}|$ between adjacent ones. The application of a longitudinal external magnetic field [Fig. 1(c)] eliminates all but the $\Delta m=\pm1$ lines but does not improve the resolution significantly. The results obtained by fitting an adequate superposition of Lorentzian lines of equal width and intensity to the spectra are compiled in Table I.

Better-resolved spectra and the sign of the hyperfine field at the Hf nuclei in $(Hf_{0.1}Zr_{0.9})Fe_2$ can be obtained by using a ferromagnetic source with a large hyperfine field H_{hf} instead of the single-line source. Then, in a longitudinal polarizing field H_{ext}, both the source and absorber spectra are doublets with the emission as well as the absorption lines circularly polarized. The Mössbauer spectrum consists of two lines with a separation $2\Delta=2|\Delta^S(2^+)-\Delta^A(2^+)|=2|g(2^+)\mu_N(H_{eff}{}^S-H_{eff}{}^A)|$, where $H_{eff}=H_{hf}+H_d+H_{ext}$ is the effective field at the nucleus, H_d is the demagnetizing field, and S and A refer to source and absorber, respectively. If H_{hf} is sufficiently large, the doublet is resolved and Δ can be accurately measured. The field $H_{hf}{}^S$ can be measured independently with a nonmagnetic single-line absorber. Since the demagnetizing fields can be estimated with sufficient accuracy, $H_{hf}{}^A$ can then be calculated. A suitable source[5] for this kind of measurement is Ta in a Fe matrix. Disks of a $Ta_{0.002}$-$Fe_{0.998}$ alloy were exposed to the bremsstrahlung and then used as Mössbauer sources. Figure 1(d) shows a spectrum of such a source taken with a $HfZn_2$ single-line absorber and no external field.

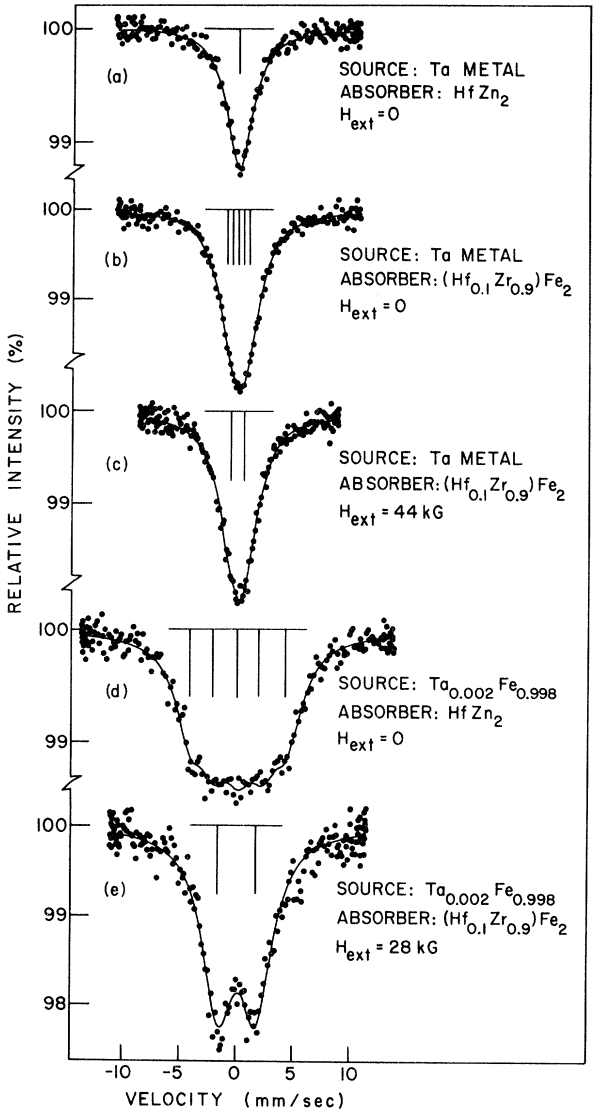

FIG. 1. Transmission Mössbauer spectra of the 93.3-keV γ rays of ^{180}Hf. The spectra were taken with the indicated sources and absorbers at 4.2 K, and with the external field H_{ext} applied to both source and absorber.

From this spectrum the hyperfine field H_{hf}^{s} in the source was derived. The spectrum obtained with a $Ta_{0.002}Fe_{0.998}$ source and a $(Hf_{0.1}Zr_{0.9})Fe_2$ absorber, both in a polarizing field of 28 kOe [Fig. 1(e)], is a resolved doublet. The hyperfine splitting Δ derived from these data is smaller than $\Delta(2^+)$ found for the $Ta_{0.002}Fe_{0.998}$ source. This shows that the hyperfine field in the intermetallic compound has the same sign as the field at Hf in Fe, which is negative.[6] Our measurements thus confirm the negative sign for the irregular $E2/M2$ mixing ratio, which Krane *et al.*[1] had to infer from circular polarization data[2] on the decay of ^{180m}Hf. The hyperfine-field values given in Table I were calculated from the individual experimental results with $g(2^+) = +0.263 \pm 0.015$.[7] The demagnetizing fields used, $H_d^{\,s} = -17$ kOe and $H_d^{\,A} = -5$ kOe for the $Ta_{0.002}Fe_{0.998}$ sources and $(Hf_{0.1}Zr_{0.9})Fe_2$ absorbers, respectively, were estimated from the bulk saturation magnetization[8] of $ZrFe_2$ and of Fe, with allowance for the shapes of the samples and the actual density of the powder absorbers.

Finally, the average of the individual results on $(Hf_{0.1}Zr_{0.9})Fe_2$ is $\Delta(2^+) = -(1.67 \pm 0.15)\times 10^{-7}$ eV and $H_{hf} = -200 \pm 20$ kOe. This value for H_{hf} is slightly smaller than the hyperfine field obtained from the Mössbauer data of Snyder, Ross, and Bunbury[9] for the more Hf-rich compound $(Hf_{0.5}Zr_{0.5})Fe_2$ with the $g(2^+)$ factor of Ref. 7. For the hyperfine field at Hf in a Fe matrix we obtain -796 ± 47 kOe from the hyperfine splitting $\Delta(2^+) = -(6.60 \pm 0.07)\times 10^{-7}$ eV in the $Ta_{0.002}Fe_{0.998}$ source. A comparison with the previously observed[5] splitting of the 93.2-keV state of ^{178}Hf in Fe yields $g(2^+;{}^{180}\mathrm{Hf})/g(2^+;{}^{178}\mathrm{Hf}) = 0.96 \pm 0.02$.

Using the hyperfine splitting of the 8^- state in $(Hf_{0.1}Zr_{0.9})Fe_2$ as given by Ref. 1, we derive $\mu(8^-) = +(8.6 \pm 1.0)\mu_N$ for the 1142-keV two-quasiparticle state in ^{180}Hf. According to the Nilsson scheme and from a consideration of the Nilsson assignments of the ground states and low-energy excited states in neighboring nuclei, the 8^- state is expected[10] to be either the $\{\frac{7}{2}[514], \frac{9}{2}+[624]\}_{8^-}$ two-neutron excitation or the $\{\frac{7}{2}+[404], \frac{9}{2}-[514]\}_{8^-}$ two-proton excitation. The magnetic moment to be expected in these cases can be estimated by properly adding the empirical values of the magnetic moments[11] for the corresponding orbitals in neighboring odd-A nuclei like ^{177}Hf(g.s.) and ^{179}Hf(g.s.) or ^{181}Ta(g.s.) and ^{181}Ta(6.3-keV state). This yields $|\mu(8^-)| \lesssim 0.1\mu_N$ and $\mu(8^-) = +8.2\mu_N$ for the two-neutron and the two-proton configurations, respectively. From a Nilsson-model calculation using $\eta = 4$, free-nucleon g factors, and the relation[12]

$$\mu = [I/(I+1)][g_{s1}\langle s_{z1}\rangle + g_{l1}\langle l_{z1}\rangle + g_{s2}\langle s_{z2}\rangle + g_{l2}\langle l_{z2}\rangle + g_R]\mu_N,$$

one obtains $\mu(8^-) = +7.4\mu_N$. In the asymptotic limit the spin contributions cancel each other out. This feature is almost completely preserved for all reasonable values of the nuclear deformation, and one obtains $\mu(8^-) \approx I[g_l I/(I+1) + g_R/(I+1)]$. Hence ambiguities due to spin-polarization effects would not influence the predicted values. Our experimental result thus identifies the 1142-keV 8^- state as a rather pure $\{\frac{7}{2}+[404], \frac{9}{2}-[514]\}_{8^-}$ two-proton configuration; a 10% admixture of the two-neutron configuration would already be inconsistent with our value of the magnetic moment. This situation is different from that in ^{178}Hf, for which both 8^- states are known and a rather large mixing of the two states has to be assumed in order to explain the logft values.[10]

Since spin magnetism does not contribute significantly to the magnetic moment of the 8^- state in ^{180}Hf, this state seems to be a favorable case for the detection of an anomalous orbital contribution[13] to magnetic moments. Indeed, a comparison of our experimental value with the model prediction would result in a value of $g_l = 1.16 \pm 0.12$, but the experimental errors are still too large for any definite conclusion.

Because of the uncertainties inherent in the determination of hyperfine fields from poorly resolved Mössbauer spectra, it seems very difficult to increase substantially the accuracy of the hyperfine field value for $(Hf_{0.1}Zr_{0.9})Fe_2$. It should, however, be possible to obtain a more accurate value for $\mu(8^-)$ by repeating the nuclear polarization experiments with ^{180m}Hf in an iron matrix, where the hyperfine interaction of the 2^+ state at 4.2 K is known from previous Mössbauer measurements[5] and the present work. The error of $\mu(8^-)$ would then virtually be determined only by the errors of the $g(2^+)$ factors and by the accuracy with which $\Delta(8^-)$ can be measured.

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