effective charge on the ferrous ion to be 1.8,[31] and accounting for the four unpaired electrons of the ^5D state, one obtains $\alpha^2=0.95$ for $Fe(H_2O)_6^{++}$.

In further support of the above arguments, we may refer to Mössbauer studies of $Fe(H_2O)_6^{++}$ in hexagonal ice,[22] where analysis of quadrupole-splitting data yields the orbital ground state $|xy\rangle$, and a quadrupole moment of the same magnitude as derived above from $FeSiF_6\cdot 6H_2O$.

It is to be noted that the original study of Johnson, *et al.*,[19] which yielded the positive sign of Q, also mentioned carrying out a lattice sum on $FeSiF_6\cdot 6H_2O$, and found the contribution to be negligible. Apart from the small effects of q_{lat} and spin-orbit coupling which we have included, if Johnson *et al.*[19] had used the recent values of $(1-R)$ and $\langle r^{-3}\rangle$, they would have obtained a result essentially the same as Eq. (8).

The determination of Q from Mössbauer data has received much attention in the literature.[1,2,32–35] The original large deviation between the high value ($\sim$0.46 b) derived from Fe^{+3} ion in Fe_2O_3 [32] and the low value ($\sim$0.1 b) derived from Fe^{+2} in various crystals[19,33–35] had been reduced to a range of 0.2 to 0.3 b by better estimates of the quantities γ_∞, R, and $\langle r^{-3}\rangle$. The values we have used for these parameters are the best recent estimates obtained from unrestricted Hartree-Fock calculations,[2] and are the same as used by Ingalls.[3] It may be noted that our result $Q=0.20$ b agrees very well with that obtained from the Fe^{+3} case, which has been revised downward from 0.28 to 0.18 b.[2]

[32] G. Burns, Phys. Rev. **124,** 524 (1961).
[33] A. Abragam and F. Boutron, Compt. Rend. **252,** 2404 (1961).
[34] R. Ingalls, Phys. Rev. **128,** 1155 (1962).
[35] H. Eicher, Z. Physik **171,** 582 (1963).

PHYSICAL REVIEW VOLUME 159, NUMBER 2 10 JULY 1967

Stopping Powers for Iodine Ions at Energies up to 200 MeV*

L. B. Bridwell,† L. C. Northcliffe,‡ S. Datz, C. D. Moak, and H. O. Lutz
Oak Ridge National Laboratory, Oak Ridge, Tennessee

(Received 13 February 1967)

Multicomponent beams of ^{127}I ions from an MP tandem accelerator have been used to extend some earlier stopping-power measurements for C, Al, Ni, Ag, Au, and UF_4 to energies up to 200 MeV. The expected maximum values of stopping powers have been reached in some cases.

REASONABLY accurate stopping-power measurements for very heavy ions in the energy range up to 100 MeV have become available only recently with the development of new accelerator techniques.[1] The results of these measurements have been useful for the analysis of data in studies of fission and in Coulomb excitation experiments; the results have an important bearing upon the design of various kinds of accelerators for very heavy ions. A collection of much of the information available on ions of medium weight has been presented by Northcliffe.[2] Theoretical analyses and comparisons with fission-fragment data were presented by Lindhard *et al.*[3] Recent measurements have been reported for Br and I ions up to energies of 100 MeV in various solid elements and compounds.[4,5]

The present work is an extension of the energy range for ^{127}I stopping powers to 200 MeV. Multicomponent beams of ^{127}I ions from an MP tandem accelerator were used.[6] Higher terminal voltages available with this new accelerator produced the increased energy range; the experimental procedure was the same as that described earlier.[4] Energy shifts between runs with and without a foil of known thickness in place were used to estimate the stopping power dE/dx, at each energy. Foils were prepared by vacuum evaporation and thicknesses were estimated from α-particle energy-loss measurements. The new dE/dx values obtained have been added to those reported earlier and the result is shown in Fig. 1. In the region of overlap (90–110 MeV) agreement with previous results was within the over-all $\pm 10\%$ uncertainty which we estimate for these measurements. For each stopping medium the data presently obtained were normalized to obtain best fits to the earlier data since the latter had been obtained with somewhat better statistics and often with more than one foil thickness; the normalization factors were, for carbon: 0.93; Ni: 0.94; Ag: 0.90; Au: 1.14; and UF_4: 1.05.

According to Lindhard *et al.*,[3] velocity-proportional electronic stopping is to be expected in the velocity region below $v_0Z^{2/3}$, where $v_0=e^2/\hbar$, and Z is the nuclear charge of the projectile. At higher velocities the ion approaches the totally stripped condition after which

* Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.
† Summer research participant, Murray State University, Murray, Kentucky.
‡ Permanent address: Texas A&M University, College Station, Texas.
[1] C. D. Moak, J. H. Neiler, H. W. Schmitt, F. J. Walter, and G. F. Wells, Rev. Sci. Instr. **34,** 853 (1963).
[2] L. C. Northcliffe, Ann. Rev. Nucl. Sci. **13,** 67 (1963).
[3] J. Lindhard, M. Scharff, and H. E. Schiøtt, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **33,** No. 14 (1963).
[4] C. D. Moak and M. D. Brown, Phys. Rev. **149,** 244 (1966).
[5] L. B. Bridwell and C. D. Moak, Phys. Rev. **156,** 242 (1967).
[6] We are indebted to High Voltage Engineering Corporation, Burlington, Massachusetts for the use of the MP accelerator facility.

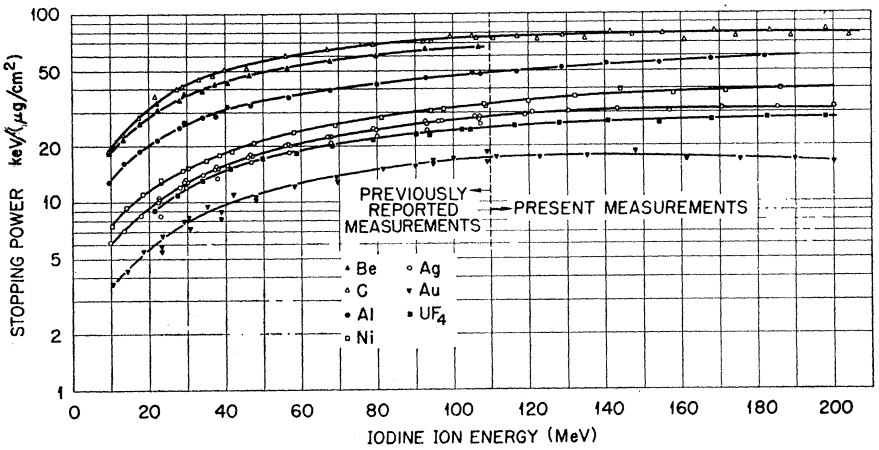

FIG. 1. Stopping power of several solid materials for iodine ions.

the stopping power is expected to decrease with velocity. It is expected that dE/dx should reach a maximum value at or below $v_0Z^{2/3}$ ($0.1c$ for ^{127}I). From the results in the figure it can be seen that this maximum has been reached in the case of Au at about 125 MeV corresponding to a velocity of $0.046c$. For the other materials measured the maxima appear to occur at somewhat higher velocities but still well below the value $v_0Z^{2/3}$.

ACKNOWLEDGMENTS

The authors are indebted to Dr. R. J. Van de Graaff, D. M. Robinson, J. F. Bromberger, and their associates for their cooperation, advice, and assistance.

PHYSICAL REVIEW VOLUME 159, NUMBER 2 10 JULY 1967

Paramagnetic Resonance and Relaxation of Some Rare-Earth Ions in $YCl_3 \cdot 6H_2O$*

M. B. SCHULZ† AND C. D. JEFFRIES
Department of Physics, University of California, Berkeley, California

(Received 10 February 1967)

The paramagnetic resonance at $\nu = 9.3$ Gc/sec has been observed at helium temperatures for Ce^{3+}, Nd^{3+}, Dy^{3+}, Er^{3+}, and Yb^{3+} diluted in single crystals of $YCl_3 \cdot 6H_2O$. The principal values g_x, g_y, and g_z of the g tensor were measured and showed marked anisotropy. The spin bath relaxation rate T_b^{-1} was measured for Nd^{3+} and Er^{3+} over the temperature range $0.2 \leqq T \leqq 5$°K and for Ce^{3+} and Dy^{3+} over the range $1.3 \leqq T \leqq 5$°K, by observing the transient recovery of the microwave resonance following a saturating pulse. The temperature dependence of the Orbach process, $T_b^{-1} \propto \exp(-\Delta/T)$, is displayed for all four ions, with values of Δ in agreement with optical measurements in concentrated crystals. There is some evidence of phonon bottlenecking of the Orbach process for Dy^{3+}. The Raman process $T_b^{-1} \propto T^9$ was observed for Ce^{3+} and Dy^{3+}. The direct process $T_b^{-1} \propto \coth(h\nu/2kT)$ was observed for all four ions, and displayed a very large anisotropy, of order 10^3 to 10^4, for Nd^{3+} and Er^{3+}, which can be approximately understood in terms of the matrix elements of the Zeeman perturbation between ground and excited states. For Nd^{3+} there was some evidence for a phonon bottleneck of the direct process, $T_b^{-1} \propto T^2$.

I. INTRODUCTION

IN a previous paper,[1] referred to as I, we reported an experimental study of spin-lattice relaxation of some rare-earth ions in the host crystal LaF_3, by observing the transient recovery of the microwave paramagnetic resonance absorption following a saturating pulse. In this paper we present very similar studies for Ce^{3+}, Nd^{3+}, Er^{3+}, and Dy^{3+} in the host crystal $YCl_3 \cdot 6H_2O$, in the temperature range 0.2–5°K in fields of a few thousand Oersteds, corresponding to a microwave frequency of $\nu = 9.3$ Gc/sec. We refer to I for notation, theory, description of the apparatus, and experimental procedures. Our interest in studying rare-earth ions in the hydrated chlorides arose in connection with nuclear-spin refrigerators,[2] in which the magnetization of a system of paramagnetic ions is cyclically transferred by crystal rotation to a nuclear-spin system, by virtue of extreme anisotropies in the paramagnetic relaxation

* Supported in part by the U.S. Atomic Energy Commission, Contract No. AT-(11-1)-34, Project 20; Report No. UCB-34P20-131 (unpublished).

† Present address: Raytheon Company, Research Division, Waltham, Massachusetts.

[1] M. B. Schulz and C. D. Jeffries, Phys. Rev. 149, 270 (1966).

[2] C. D. Jeffries, Cryogenics 3, 41 (1963); A. Abragam, *ibid.* 3, 42 (1963).