Parity-violation effect in heliumlike gadolinium and europium

L. N. Labzowsky,[1,2,3] A. V. Nefiodov,[1,2,3] G. Plunien,[4] G. Soff,[4] R. Marrus,[5]
and D. Liesen[6]
[1]Max-Planck-Institut für Physik Komplexer Systeme, Nöthnitzer Strasse 38, D-01187 Dresden, Germany
[2]St. Petersburg State University, 198904 St. Petersburg, Russia
[3]Petersburg Nuclear Physics Institute, 188300 Gatchina, St. Petersburg, Russia
[4]Institut für Theoretische Physik, Technische Universität Dresden, Mommsenstrasse 13, D-01062 Dresden, Germany
[5]Department of Physics, University of California, Berkeley, California 94720
[6]Gesellschaft für Schwerionenforschung (GSI), Planckstrasse 1, D-64291 Darmstadt, Germany
(Received 28 July 2000; published 18 April 2001)

Parity nonconservation that originates from the weak interaction of atomic electrons with the nuclei in heliumlike gadolinium and europium is considered. An experiment with a polarized ion beam is discussed. The mixed hyperfine- and weak-quenching effect in Gd^{62+} and Eu^{61+} isotopes is shown to lead to an asymmetry of the photon emission relative to the ion beam polarization. With complete beam polarization, the magnitude of the asymmetry in photon counting rates reaches about 0.39×10^{-3} in gadolinium and is about 0.11×10^{-3} in europium.

DOI: 10.1103/PhysRevA.63.054105 PACS number(s): 11.30.Er, 32.80.Ys, 32.30.Rj

Parity-nonconservation (PNC) effects in atomic systems are under intense theoretical and experimental investigation. Successful experiments have been performed with neutral Cs, Tl, Pb, and Bi atoms during the recent decades. The most accurate experiments with Cs atoms show a deviation up to 2.9σ from the standard model of electroweak interactions [1–3]. The main uncertainty results from the theoretical evaluation of PNC matrix elements that require the inclusion of electron-electron correlation effects. The most natural way to resolve this discrepancy is to turn to simpler electronic systems, in particular, to few-electron highly charged ions. In this case the PNC effects have been discussed so far only theoretically [4–10]. Unlike in neutral atoms, the major corrections to the PNC matrix elements in highly charged ions are the radiative electroweak ones. These corrections were partly calculated in Ref. [11]. Apart from the resolution of the discrepancy mentioned above, experiments with heavy ions would provide a test of the standard model in strong fields and beyond the tree level.

For experiments a most promising situation occurs in heavy two-electron ions due to the near-degeneracy of two levels with opposite parities, $2\,^1S_0$ and $2\,^3P_0$. These levels cross twice: near the nuclear charge numbers $Z=64$ (gadolinium) and $Z=92$ (uranium). The situation in uranium was studied earlier in Refs. [5,7–9]. In the present work, we consider heliumlike Gd^{62+} and Eu^{61+} ions employing an analogous scheme of the hyperfine and weak level mixing to that of Ref. [7]. However, instead of the standard measurement of circular dichroism which is rather difficult to perform with x-ray radiation, we propose a quenching-type experiment with interference of hyperfine- and weak-quenched transitions. The hyperfine-quenched (hfq) transitions in two-electron ions were observed in Refs. [12–17] with the use of a beam-foil time-of-flight technique. Similar parity-violation experiments require the use of a polarized ion beam. Up to now no parity-violation experiments with polarized electrons in atoms have been performed.

In this paper, we will focus on the spin-independent part of the weak interaction of an electron with the nucleus ($\hbar=c=1$) [18]:

$$\hat{H}_{\mathrm{w}}(\boldsymbol{r})=-\frac{G_F}{2\sqrt{2}}Q_{\mathrm{w}}\rho_N(r)\gamma_5, \tag{1}$$

where G_F is the Fermi constant, $Q_{\mathrm{w}}=Z(1-4\sin^2\theta_{\mathrm{w}})-N$ is the weak charge of the nucleus at the tree level with N being the number of neutrons, ρ_N is the nuclear density normalized to unity, and γ_5 is the Dirac matrix. The influence of radiative corrections on the matrix elements of the operator (1) has been investigated in Ref. [11].

The one-photon hfq $M1$ transition $2\,^1S_0\to1\,^1S_0$ is due to the hyperfine mixing of the $2\,^1S_0$ and $2\,^3S_1$ levels. The weak interaction of electrons with the nucleus also opens another one-photon decay channel $2\,^1S_0\to1\,^1S_0$ through the mixing of the $2\,^1S_0$ and $2\,^3P_0$ levels by the operator $\hat{H}_{\mathrm{w}}$ and due to the hyperfine mixing of the $2\,^3P_0$ and $2\,^3P_1$ states. As a result, the total amplitude of the one-photon transition $2\,^1S_0\to1\,^1S_0$ is represented by a mixture of the basic $M1$ and of the additional $E1$ amplitudes. After angular integration, it can be written in matrix form as

$$\mathcal{A}=\frac{\sqrt{2}}{\sqrt{I(I+1)}}\{\xi_s\mathcal{A}_s(\boldsymbol{I}\cdot[\boldsymbol{e}^*\times\boldsymbol{n}])-i\eta\xi_p\mathcal{A}_p(\boldsymbol{I}\cdot\boldsymbol{e}^*)\}, \tag{2}$$

where $\boldsymbol{I}$ is the operator of the total angular momentum of the ion and $\boldsymbol{e}$ is the polarization vector of a photon emitted in the direction $\boldsymbol{n}=\boldsymbol{k}/\omega_0$. The values $\mathcal{A}_s$ and $\mathcal{A}_p$ are the radial parts of $M1$ $2\,^3S_1\to1\,^1S_0$ and $E1$ $2\,^3P_1\to1\,^1S_0$ amplitudes, respectively. They are both calculated at the same transition frequency $\omega_0=E_{2\,^1S_0}-E_{1\,^1S_0}$:

$$\mathcal{A}_s=i\sqrt{4\pi\alpha}\int_0^\infty dr\, j_1(\omega_0 r)[P_{1s}(r)Q_{2s}(r)+P_{2s}(r)Q_{1s}(r)], \tag{3}$$

TABLE I. Listed are isotopes of europium and gadolinium, their abundances (in %), nuclear spins I, nuclear magnetic dipole moments μ in units of nuclear magnetons μ_N (taken from Ref. [20]), hyperfine mixing coefficients ξ_s and ξ_p, hfq transition rates W_s and W_p, and weak mixing factors η.

Nucleus	Abundance	I	μ/μ_N	ξ_s	ξ_p	W_s (s^{-1})	W_p (s^{-1})	η
${}^{151}_{63}$Eu	47.8	5/2	$+3.4717$	-0.583×10^{-2}	-0.424×10^{-1}	0.68×10^{8}	0.11×10^{14}	0.33×10^{-6}
${}^{153}_{63}$Eu	52.2	5/2	$+1.5330$	-0.257×10^{-2}	-0.187×10^{-1}	0.13×10^{8}	0.22×10^{13}	0.33×10^{-6}
${}^{155}_{64}$Gd	14.8	3/2	-0.2591	0.489×10^{-3}	0.335×10^{-2}	0.58×10^{6}	0.75×10^{11}	0.91×10^{-6}
${}^{157}_{64}$Gd	15.65	3/2	-0.3398	0.642×10^{-3}	0.439×10^{-2}	0.99×10^{6}	0.13×10^{12}	0.91×10^{-6}

$$\mathcal{A}_p = i\sqrt{4\pi\alpha}\int_0^\infty dr\left[j_0(\omega_0 r)P_{1s}(r)Q_{2p_{1/2}}(r) - \frac{1}{3}[2j_2(\omega_0 r) - j_0(\omega_0 r)]P_{2p_{1/2}}(r)Q_{1s}(r)\right]. \tag{4}$$

Here $P_{nlj}(r)$ and $Q_{nlj}(r)$ denote the upper and lower radial components of the electron wave function, respectively, α is the fine-structure constant, and $j_l(x)$ are the spherical Bessel functions.

The weak mixing coefficient in Eq. (2) is determined by

$$i\eta = \Delta_0^{-1}\langle 2\,{}^3P_0|\hat{H}_{\mathrm{w}}|2\,{}^1S_0\rangle = -i\frac{G_F}{2\sqrt{2}}\frac{Q_{\mathrm{w}}}{\Delta_0}R_{sp}, \tag{5}$$

$$R_{sp} = \frac{1}{4\pi R_0^2}[P_{2s}(R_0)Q_{2p_{1/2}}(R_0) - P_{2p_{1/2}}(R_0)Q_{2s}(R_0)],$$

where $\Delta_0 = E_{2\,{}^1S_0} - E_{2\,{}^3P_0}$ and $R_0 = 1.2A^{1/3}$ fm estimates the nuclear radius for an isotope with mass number A. The mixing coefficients due to the hyperfine magnetic-dipole interaction operator $\hat{H}_{\mathrm{hfs}}$ are

$$\begin{aligned}\xi_s &= \Delta_s^{-1}\langle 2\,{}^3S_1|\hat{H}_{\mathrm{hfs}}|2\,{}^1S_0\rangle\\ &= \frac{g_I}{\Delta_s}\frac{2\alpha}{3m_p}\sqrt{I(I+1)}\int_0^\infty \frac{dr}{r^2}[P_{1s}(r)Q_{1s}(r) - P_{2s}(r)Q_{2s}(r)]\\ &= -\alpha(\alpha Z)^3\frac{g_I}{\Delta_s}\frac{2m_e^2}{3m_p}\sqrt{I(I+1)}\left[\frac{(1-\delta_{1s})}{\gamma(2\gamma-1)} - \frac{(2\gamma+2+\sqrt{2\gamma+2})}{(2\gamma+2)^2\gamma(4\gamma^2-1)}(1-\delta_{2s})\right],\end{aligned} \tag{6}$$

$$\begin{aligned}\xi_p &= \Delta_p^{-1}\langle 2\,{}^3P_1|\hat{H}_{\mathrm{hfs}}|2\,{}^3P_0\rangle\\ &= \frac{g_I}{\Delta_p}\frac{2\alpha}{3m_p}\sqrt{I(I+1)}\int_0^\infty \frac{dr}{r^2}[P_{1s}(r)Q_{1s}(r) + P_{2p_{1/2}}(r)Q_{2p_{1/2}}(r)]\\ &= -\alpha(\alpha Z)^3\frac{g_I}{\Delta_p}\frac{2m_e^2}{3m_p}\sqrt{I(I+1)}\left[\frac{(1-\delta_{1s})}{\gamma(2\gamma-1)} - \frac{(2\gamma+2-\sqrt{2\gamma+2})}{(2\gamma+2)^2\gamma(4\gamma^2-1)}(1-\delta_{2p_{1/2}})\right],\end{aligned} \tag{7}$$

where $\gamma = \sqrt{1-(\alpha Z)^2}$, m_p is the proton mass, m_e is the electron mass, $\Delta_s = E_{2\,{}^1S_0} - E_{2\,{}^3S_1}$, $\Delta_p = E_{2\,{}^3P_0} - E_{2\,{}^3P_1}$, and g_I is the nuclear g factor. The corrections δ_{nlj} account for the finite nuclear charge distribution.

The polarization of the heliumlike ion in the $2\,{}^1S_0$ state is described by the density matrix

$$\rho = \frac{1}{2I+1}\left[1 + \frac{3\lambda_0}{(I+1)}(\boldsymbol{\zeta}\cdot\boldsymbol{I})\right], \tag{8}$$

where $\boldsymbol{\zeta}$ is the unit vector in the direction of polarization of the ion, and λ_0 is the degree of polarization ($\lambda_0 \leqslant 1$). Then the probability for the emission of a photon with polarization $\boldsymbol{e}$ in direction $\boldsymbol{n}$ is evaluated according to

$$dW(\boldsymbol{n},\boldsymbol{e}) = \frac{\omega_0}{8\pi^2}\mathrm{Tr}\{\mathcal{A}\rho\mathcal{A}^\dagger\}d\Omega, \tag{9}$$

where the amplitude $\mathcal{A}$ in matrix form (2) is used. After some transformations and summation over the polarizations of a photon in Eq. (9), one obtains

$$dW(\boldsymbol{n}) = \frac{W_s}{4\pi}[1 + \varepsilon(\boldsymbol{\zeta}\cdot\boldsymbol{n})]d\Omega. \tag{10}$$

Here $\varepsilon = 3\lambda_0\eta R/(I+1)$ is the coefficient of asymmetry and $R = \sqrt{W_p/W_s}$. The total probabilities of the one-photon hfq $M1$ $2\,{}^1S_0 \to 1\,{}^1S_0$ and $E1$ $2\,{}^3P_0 \to 1\,{}^1S_0$ transitions are defined as $W_i = (2\omega_0/3\pi)\xi_i^2|\mathcal{A}_i|^2$ ($i = s,p$), where $\mathcal{A}_s$ and $\mathcal{A}_p$ are given by Eqs. (3) and (4), respectively. The experiment itself should consist of observing the difference ε in the counting rates of the quenched one-photon $2\,{}^1S_0 \to 1\,{}^1S_0$ transitions after changing the direction $\boldsymbol{\zeta}$ of ion polarization or, equivalently, after rotating the detector around the beam direction by an angle π. Correlations of the type $(\boldsymbol{\zeta}\cdot\boldsymbol{n})$ were also considered for mesic atoms in Ref. [19].

In this paper, we have investigated the quenched decay of the $2\,{}^1S_0$ level in the stable isotopes of gadolinium and europium with nonzero nuclear spins. The parameters of the ions under consideration are listed in Table I. The advantage of the proposed experiment is mainly due to the close degeneracy of levels. The level schemes for the first excited states in Gd^{62+} and Eu^{61+} ions are depicted in Figs. 1 and 2, re-

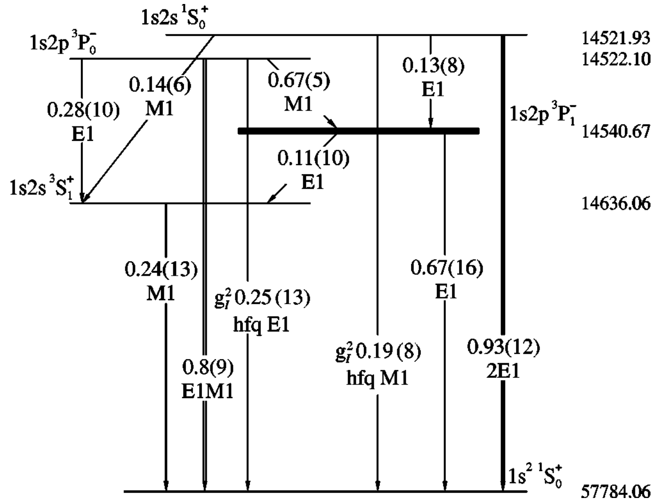

FIG. 1. Energy level scheme of the first excited states of heliumlike gadolinium. Numbers on the right-hand side indicate the ionization energies in eV. The partial probabilities of radiative transitions are given in s^{-1}. Numbers in parentheses indicate powers of 10. The large radiative width for the $1s2p\ ^3P_1$ state is indicated as a bold line. The double lines denote two-photon transitions.

spectively. The ionization energies are taken from Ref. [21]. The results of theoretical evaluations for gadolinium are in fair agreement with experimental data [15]. The one-photon transition probabilities are calculated by means of Dirac-Coulomb wave functions. Our results are in agreement with those obtained by Johnson *et al.* [22]. The $2E1$ two-photon transition rates are taken from Ref. [23]. The estimates for the $E1M1$ transition probabilities were deduced from the corresponding value for heliumlike uranium [24] via scaling in Z. For evaluation of the hyperfine mixing coefficients the finite-size corrections δ_{nlj} have been estimated according to the results of Ref. [25]. Note that our values for the coefficients (7) for Gd^{62+} and Eu^{61+} are in perfect agreement with those obtained by more refined calculations [15,26].

In gadolinium, the weak matrix element turns out to be $i\eta\Delta_0 = i0.155\times10^{-6}$ eV. In this calculation we put $\sin^2\theta_{\rm w}=0.2312$ (see Ref. [27]). The effect arising from the difference between the nuclear weak charges of two isotopes $^{155}_{64}$Gd and $^{157}_{64}$Gd is rather small and therefore negligible. The total asymmetry effect turns out to be $\varepsilon \simeq 0.39\lambda_0\times10^{-3}$, which is unusually large for parity-violation experiments. However, one should note that the lifetime of the $2\ ^1S_0$ level defined by the $2E1$ two-photon transition is about one order of magnitude smaller than the hfq $2\ ^3P_0$ lifetime. This implies a strong background in experiments with Gd^{62+} ions.

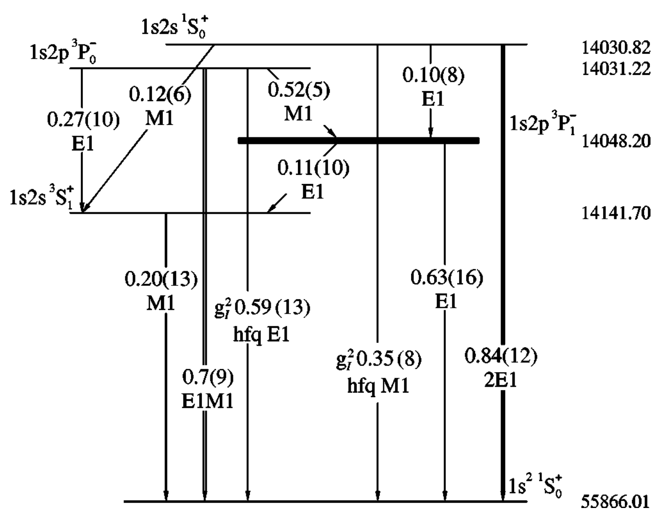

FIG. 2. Energy level scheme of the first excited states of heliumlike europium. Notations are the same as in Fig. 1.

In europium, the situation is different. The weak asymmetry effect reduces to $\varepsilon \simeq 0.11\lambda_0\times10^{-3}$. However, the $2\ ^1S_0$ level lives significantly longer then the hfq $2\ ^3P_0$ level. The $2\ ^1S_0$ lifetime equals about 1.19 ps and corresponds to a decay length of about 0.1 mm in the laboratory. The peculiarity of the situation is that unlike in standard hfq experiments we are not aiming at the measurement of the lifetime defined in our case by the two-photon transition. The experiment should result in measurement of the ratio $\Delta n/n_0$, where $n_0 \pm \Delta n$ are the numbers of counts for two directions $\boldsymbol{\zeta}$ of the beam polarization. This ratio is directly proportional to the weak interaction matrix element: $\Delta n/n_0 = \varepsilon$.

Since the photons observed in this experiment originate from single-photon decays of the hyperfine and weak mixed $F=I$ state, the success of the experiment will depend on the production of a significant degree of polarization of this state of the heliumlike ion (actually nuclear polarization). Polarized hydrogenlike ions can be produced by capture from a gas of polarized hydrogen [28,29]. By means of this method, a degree of polarization for the target of about 80% is presently achievable, and it is expected that almost 100% polarization will be achieved in the near future [30]. Then passing a polarized beam through a foil to capture an unpolarized electron into the $F=I$ state will still result in an ion (nuclear) polarization. The reason is that due to the strong hyperfine interaction the nuclei in the polarized H-like ions will also be polarized. The depolarization time ($\sim 10^{-15}$ s) is defined by the hyperfine interaction energy of about 1 eV, and it is much larger than the time of formation of the 2^1S_0 state ($\sim 10^{-18}$ s) through the capture process. The latter time is defined by the interelectron interaction energy of about 1 keV. Thus during the capture process the nuclear polarization will not be destroyed.

To observe a signal from a PNC effect of the order of $0.11\lambda_0\times10^{-3}$ with $\lambda_0 \simeq 1$ over the level of fluctuations, one needs at least 10^7 events. The efficiency of the photon detector limited only by the solid angle in this case is of the order 10^{-3}. Assuming a statistical distribution of the population of all L_{12} subshell levels and taking into account the branching ratio of 10^{-4} for the hfq decay compared to the $2E1$ transition, one obtains the total loss in statistics of about 10^{-8}. With reasonable beam intensity ($\sim 10^{10}$ ions/s) for the SIS/ESR facility at GSI in Darmstadt one finds a realistic observation time of about 10^5 s. Thus verification of the predicted effect becomes feasible by utilizing the beam-foil time-of-flight technique.

The authors are indebted to F. Bosch, H. Schmidt-Böcking, and Th. Stöhlker for useful discussions. L.L. and

A.N. are grateful to the Technische Universität Dresden and the Max-Planck-Institut für Physik komplexer Systeme (MPI) for hospitality and acknowledge financial support from the MPI, DFG, and RFBR (Grant No. 99-02-18526). L.L. and A.N. acknowledge also the hospitality of the Atomic Physics Group during their visits at GSI. G.S. and G.P. acknowledge financial support from BMBF, DFG, and GSI. A. N. acknowledges also support from the Alexander von Humboldt Foundation.

[1] S.C. Bennett and C.E. Wieman, Phys. Rev. Lett. **82**, 2484 (1999); **82**, 4153(E) (1999); **83**, 889 (1999).
[2] A. Derevianko, Phys. Rev. Lett. **85**, 1618 (2000).
[3] V.A. Dzuba and V.V. Flambaum, Phys. Rev. A **62**, 052101 (2000).
[4] V.G. Gorshkov and L.N. Labzowsky, Pis'ma Zh. Éksp. Teor. Fiz. **19**, 768 (1974) [JETP Lett. **19**, 394 (1974)].
[5] A. Schäfer, G. Soff, P. Indelicato, B. Müller, and W. Greiner, Phys. Rev. A **40**, 7362 (1989).
[6] G. von Oppen, Z. Phys. D: At., Mol. Clusters **21**, S181 (1991).
[7] V.V. Karasiev, L.N. Labzowsky, and A.V. Nefiodov, Phys. Lett. A **172**, 62 (1992).
[8] M.S. Pindzola, Phys. Rev. A **47**, 4856 (1993).
[9] R.W. Dunford, Phys. Rev. A **54**, 3820 (1996).
[10] M. Zolotorev and D. Budker, Phys. Rev. Lett. **78**, 4717 (1997).
[11] I. Bednyakov, L. Labzowsky, G. Plunien, G. Soff, and V. Karasiev, Phys. Rev. A **61**, 012103 (1999).
[12] H. Gould, R. Marrus, and P.J. Mohr, Phys. Rev. Lett. **33**, 676 (1974).
[13] R. Marrus, A. Simionovici, P. Indelicato, D.D. Dietrich, P. Charles, J.-P. Briand, K. Finlayson, F. Bosch, D. Liesen, and F. Parente, Phys. Rev. Lett. **63**, 502 (1989).
[14] R.W. Dunford, C.J. Liu, J. Last, N. Berrah-Mansour, R. Vondrasek, D.A. Church, and L.J. Curtis, Phys. Rev. A **44**, 764 (1991).
[15] P. Indelicato, B.B. Birkett, J.-P. Briand, P. Charles, D.D. Dietrich, R. Marrus, and A. Simionovici, Phys. Rev. Lett. **68**, 1307 (1992).
[16] B.B. Birkett, J.-P. Briand, P. Charles, D.D. Dietrich, K. Finlayson, P. Indelicato, D. Liesen, R. Marrus, and A. Simionovici, Phys. Rev. A **47**, R2454 (1993).
[17] A. Simionovici, B.B. Birkett, J.-P. Briand, P. Charles, D.D. Dietrich, K. Finlayson, P. Indelicato, D. Liesen, and R. Marrus, Phys. Rev. A **48**, 1695 (1993).
[18] I.B. Khriplovich, *Parity Nonconservation in Atomic Phenomena* (Gordon and Breach, New York, 1991).
[19] A.N. Moskalev and R.M. Ryndin, Yad. Fiz. **22**, 147 (1975) [Sov. J. Nucl. Phys. **22**, 71 (1976)].
[20] *Table of Isotopes*, edited by R.B. Firestone *et al.* (Wiley, New York, 1999), Vol. 2.
[21] D.R. Plante, W.R. Johnson, and J. Sapirstein, Phys. Rev. A **49**, 3519 (1994).
[22] W.R. Johnson, D.R. Plante, and J. Sapirstein, Adv. At. Mol. Opt. Phys. **35**, 255 (1995).
[23] A. Derevianko and W.R. Johnson, Phys. Rev. A **56**, 1288 (1997).
[24] G.W.F. Drake, Nucl. Instrum. Methods Phys. Res. B **9**, 465 (1985).
[25] V.M. Shabaev, J. Phys. B **27**, 5825 (1994).
[26] P. Indelicato, F. Parente, and R. Marrus, Phys. Rev. A **40**, 3505 (1989).
[27] Particle Data Group, C. Caso *et al.* Eur. Phys. J. C **3**, 1 (1998).
[28] C.J. Horowitz and H.O. Meyer, Phys. Rev. Lett. **72**, 3981 (1994).
[29] W. Haeberli, Nucl. Phys. A **626**, 103c (1997).
[30] H. Schmidt-Böcking (private communication).