Vol. 30 (1999) ACTA PHYSICA POLONICA B No 3

NUCLEI FAR FROM β–STABILITY WITHIN RELATIVISTIC MEAN FIELD THEORY* **

M. Warda, B. Nerlo-Pomorska and K. Pomorski

Theoretical Physics Department, Maria Curie-Sklodowska University
Curie-Sklodowska 1, 20-031 Lublin, Poland

(Received December 1, 1998)

The binding energies, neutron and proton separation energies, shapes and sizes of even-even β–stable nuclei with $A \geq 40$ and a few chains of isotopes with $Z = 50, 56, 82, 94$ protons and isotones with $N = 50, 82, 126$ neutrons are studied within the relativistic mean field theory.

PACS numbers: 21.60.–n, 11.10.Ef, 21.10.Ft, 21.10.Gv

1. Introduction

The experimental data [1] concerning the ground states of β-stable nuclei are usually well reproduced by any theoretical model, which parameters base on the fit of masses, proton or neutron separation energies or energy gaps of even systems or transition probabilities between rotational states. The problems appear when reaching the drip lines. The nuclei with large neutron or proton excess with respect to the β–stability line are not very stable and they are not easy to measure or to describe theoretically as well. Especially the features concerning sizes and deformations of such exotic nuclei show new qualitative behavior in dependence on neutron N or proton Z number and one has to revise not only the fenemenological parameters of the theoretical models but also our understanding of more fundamental properties like incompressibility of nuclear matter, charge independence of nuclear forces influencing the density distribution in an nucleus. We have analyzed some theoretical models as the microscopic-macroscopic Strutinsky method with various liquid drop terms and single-particle potentials [2], the

* Presented at the XXXIII Zakopane School of Physics, Zakopane, Poland, September 1–9, 1998.

** This work is partly supported by the Polish Committee of Scientific Research under Contract No. 2 P03B 049 09.

Hartree-Fock procedure with the the Gogny or Skyrme effective nuclear interaction [3] and the relativistic mean field theory (RMFT) [2, 3] presenting the quality of commonly used parameter sets for reproducing the existing experimental data.

The last proposals as the new set of optimal parameters of Woods-Saxon potential [4], the isospin dependent set [5] for Skyrme forces or the NL-3 parameters [6] for RMFT take already into account the properties of nuclei close to the drip lines. The NL-3 set was in details checked for the proton and neutron radii analysis [7] and it was used to find the simple formula for the neutron density distribution radius.

The aim of present work is to complete the conclusions of Ref. [7] for radii by the results concerning the other properties of the ground state of even–even nuclei spread all over the periodic system. The calculation was made for all β-stable nuclei and all potentially existing (bound) isotopes of Sn, Ba, Pb and Pu and isotones with $N = 50$, 82, 126. These nuclides were used in Ref. [7] to find some relations between proton and neutron radii and they serve here as the basis of the ground state properties analysis. For example the results for Pu isotopes and $N = 126$ isotones are illustrated.

As one of the best theoretical models the relativistic mean field theory is chosen in the present investigation. The basic definitions and theoretical results in comparison with experimental data are shown in Section 2. The conclusions and further investigation plans are gathered in the end of the paper.

2. Theoretical model

The relativistic mean field theory [8, 9] bases on the Dirac equation for barions and Klein–Gordon one for mesons. A nucleus is treated as the set of nucleons interacting by the exchange of mesons and described by Dirac spinors. The attraction of nucleons is caused by the scalar meson σ ($I^\pi = 0^+, T = 0$) field. The short repulsive interaction is connected with the exchange of vector meson ω ($I^\pi = 1, T = 0$). The isovector meson ρ ($I^\pi = 0^-, T = 1$) is also included. The electromagnetic interaction is carried by photons in vector A field. The selfconcistent mean field approximation is used here to solve the Dirac equations for the nucleon spinors and the Klein–Gordon equation for the meson fields. When selfconcistency is reached we add the short range correlations between protons and between neutrons using the monopole pairing forces and the BCS formalism.

The BCS wave function of the ground state is constructed from the selfconcistent single particle neutron and proton states

$$\Psi = \sum_\nu (u_\nu + v_\nu a_\nu^+ a_{-\nu}) |\mathrm{vac}\rangle \ . \tag{1}$$

The strength of the pairing interaction is fixed from the experimental energy gaps Δ [1], where the masses are available or from $\Delta = 12/\sqrt{A}$ MeV in other cases.

We have performed the calculation of the following observables, characterizing main properties of the ground state of even–even nuclei:

- binding energy $B_{\rm RMF}$,
- separation energies S_p, S_n,
- proton and neutron radii

$$r^2_{p(n)} = \langle\Psi|\sum_\nu r^2_\nu|\Psi\rangle^{p(n)} = \frac{1}{Z}\left(\frac{1}{N}\right) Q_0^{p(n)} \ , \tag{2}$$

- quadrupole moments of proton and neutron distributions

$$Q_2^{p(n)} = \langle\Psi|\sum_\nu r^2_\nu P_2(\cos\theta)|\Psi\rangle^{p(n)} \ , \tag{3}$$

- reduced transition probabilities

$$B(E2) = \sqrt{\frac{5}{16\pi}}(Q_2^p)^2 \ , \tag{4}$$

- and quadrupole deformations of proton and neutron distributions

$$\beta_2^{p(n)} = \sqrt{\frac{4\pi}{5}}\,\frac{Q_2^{p(n)}}{Q_0^{p(n)}} \, . \tag{5}$$

The above quantities are analyzed in order to describe the proton and neutron density distributions in a nucleus, its size, deformation and stability.

In Figs. 1 and 2 the typical sets of results of the RMFT calculations are presented as functions of mass number A. We have chosen here a chain of isotopes of plutonium $Z = 94$ (Fig. 1) and a chain of isotones with $N = 126$ (Fig.2).

The upper left part of each figure shows the difference between the binding energy $B_{\rm RMF}$ of a nucleus calculated by the RMFT with the NL-3 parameters set and its experimental value $B_{\rm exp}$ taken from [1]. Usually the maximal error of the RMFT estimates does not exceed 5 MeV, only for the heaviest $N = 126$ isotones the error is larger.

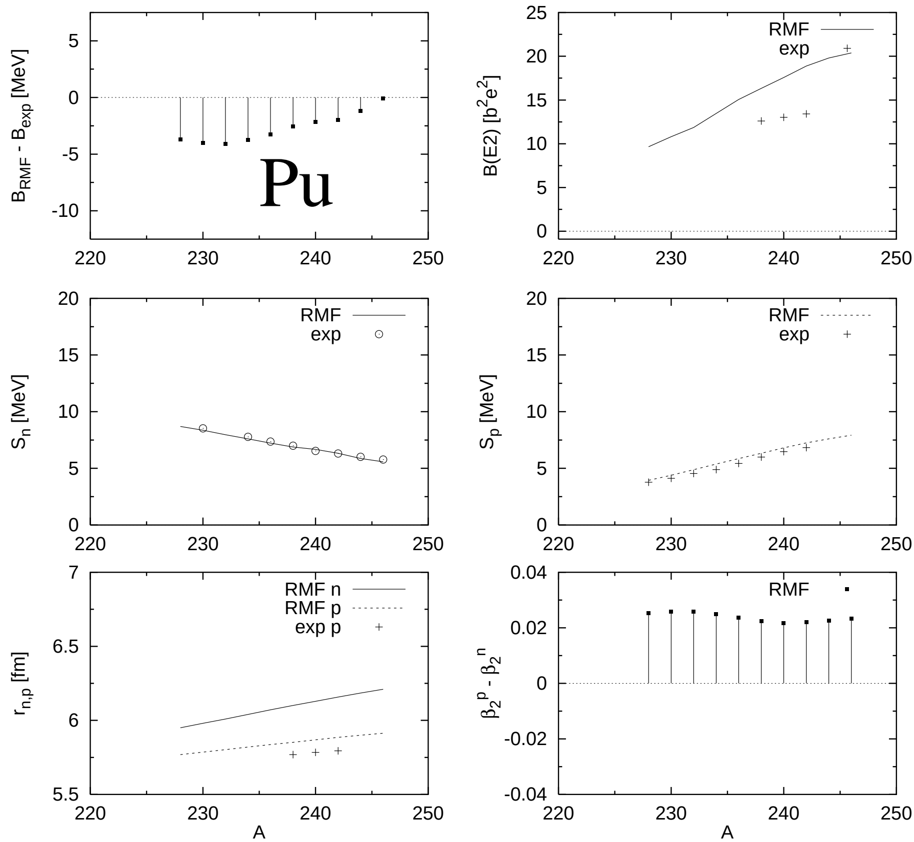

Fig. 1. The results obtained within the RMFT+BCS model with the NL-3 parameters [6] for the plutonium isotopes ($Z = 94$) compared with the experimental data as functions of mass number A. In the diagrams are presented: the difference between the calculated $B_{\rm RMF}$ and experimental $B_{\rm exp}$ binding energy (upper-left figure), reduced electric quadrupole transition probabilities $B(E2)$ (upper-right figure), neutron and proton separation energies S_n, S_p (middle figures), neutron and proton root mean square radii r_n, r_p (lower-left figure), differences between proton and neutron quadrupole deformation parameters $\beta_2^p - \beta_2^n$ (lower-right figure).

The upper right figure presents the reduced electric quadrupole transition probabilities $B(E2)$ obtained by the RMFT (solid line) compared to the experimental data [13] (crosses). Generally the agreement is rather good in spite of too large theoretical predictions of the nuclei about $A \sim 170$ and 240.

The separation energies presented in the middle pair of figures for neutron S_n (left hand side) and for proton S_p (right hand side) evaluated within

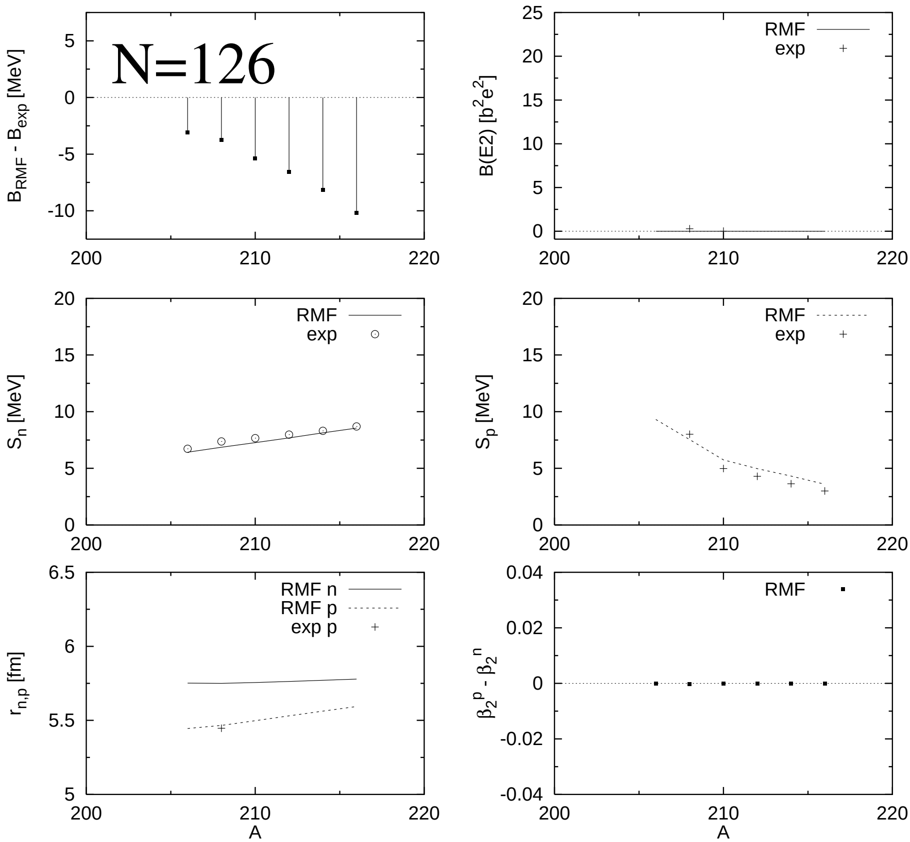

Fig. 2. Same as in Fig. 2 but for the isotones with $N = 126$.

the RMFT (solid lines) agree with the experimental data [1] (circles and crosses) very well.

The neutron r_n and proton r_p root mean square radii [7] calculated by the RMFT presented in the lowest left hand side of the figures are also close to the experimental data (crosses for protons [10, 11]). The both radii are slightly different from each other, what is connected with the different in size and in deformation proton and neutron density distributions. The neutron radii are measured in a few cases only [12] and theoretical prediction for them lies always very close to experimental data. Only for ^{208}Pb some discrepancy ($\sim$0.05 fm) is noticed.

The difference of the proton and neutron quadrupole deformations obtained in the RMFT calculation is shown in the lowest right part of the figures. One can see that for some nuclei it reaches even 0.03 but for spherical $N = 126$ isotones the both distributions differ only in size.

3. Conclusions

The results of our calculation confirm the high predictive power of the NL-3 [6] set of RMFT parameters. The experimental data like binding energies, neutron and proton separation energies are well reproduced even for nuclei far from β–stability. A significant differences in size and deformation between the proton and neutron distribution is foreseen. The mean square charge radii and neutron distribution radii are well reproduced within the RMFT model.

Nevertheless more detailed experimental evidence of nuclear properties close to the drip lines will be appreciated. Especially experiments manifesting the difference in the deformations of proton and neutron distribution will be welcome.

The authors gratefully acknowledge the numerical code for solving the relativistic Hartree model and the helpful discussions with Peter Ring.

REFERENCES

[1] G. Audi, A. H. Wapstra, *Nucl. Phys.* **A595**, 409 (1995).

[2] K. Pomorski, P. Ring, G. A. Lalazissis, A. Baran, Z. Łojewski, B. Nerlo-Pomorska, M. Warda, *Nucl. Phys.* **A624**, 329 (1997).

[3] A. Baran, J. L. Egido, B. Nerlo-Pomorska, K. Pomorski, P. Ring, L. M. Robledo, *J. Phys.* **G21**, 657 (1995).

[4] Z. Łojewski, J.Dudek, *Acta Phys. Pol.* **B29**, 407 (1998).

[5] P.G. Reinhard, H. Flocard, *Nucl. Phys.* **A584**, 467 (1995), and references therein.

[6] G.A. Lalazissis, C.P. Panes, M.E. Grypeos, Y.K. Gambhir, *Z. Phys.* **A357**, 429 (1997).

[7] M. Warda, B. Nerlo-Pomorska, K. Pomorski, *Nucl. Phys.* **A635**, 484 (1998).

[8] B.D. Serot, J.D. Walecka, *Adv. Nucl. Phys.* **16**, 1 (1997).

[9] P. Ring, *Prog. Part. Nucl. Phys.* **37**, 193 (1996).

[10] E.G. Nadjakov, K.P. Marinova, *At. Data and Nucl. Data Tables* **56**, 133 (1994).

[11] K. Heilig, A. Steudel, *At. Data and Nucl. Data Tables* **14**, 613 (1974).

[12] C.J. Batty, E. Friedman, H.J. Gils, H. Rebel, *At. Data and Nucl. Data Tables* **36**, 49 (1987).

[13] E.W. Otten, *Treatise on Heavy Ion Science*, Vol. **8**, D.A. Bromley (Ed.), Plenum Press, New York 1989, p. 517.