\(\eta\)-mesic nuclei in relativistic mean-field theory

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Abstract – With the \(\eta\)-nucleon (\(\eta N\)) interaction Lagrangian deduced from chiral perturbation theory, we study the possible \(\eta\)-mesic nuclei in the framework of relativistic mean-field theory. The \(\eta\) single-particle energies are sensitive to the \(\eta N\) scattering length, and increase monotonically with the nucleon number \(A\). If the scattering length is in the range of \(a_{\eta N} \approx 0.75\)–1.05 fm and the imaginary potential \(V_0 \approx 15\) MeV, some discrete states of \(^{12}\text{C},^{16}\text{O}\) and \(^{20}\text{Ne}\) should be identified in experiments. However, when the scattering length \(a_{\eta N} < 0.5\) fm, or the imaginary potential \(V_0 > 30\) MeV, no discrete \(\eta\)-meson bound states could be observed in experiments.

Introduction. – Since the \(\eta\)-mesic nuclei were predicted by Haider et al. [1,2], the topics on the \(\eta N\) interactions and \(\eta\)-mesic nuclei are studied extensively. Although all of the theory models predict that the interaction between \(\eta\) meson and nucleon is attractive, its strength (i.e. the predicted \(\eta\) nuclear potential) has strong model dependence and spans from about \(\sim 20\) MeV to \(\sim 100\) MeV [3–6].

Because of the uncertainties of the \(\eta\) nuclear potentials, the predictions of the \(\eta\)-mesic nuclei are very different in different models [1,7–19]. For example, some models predicted that \(\eta\)-mesic nuclei could be found in the nuclei with nucleon number \(A > 10\) [1], while some other models predicted that they could be found in very light nuclei with \(A \geq 2\) [15–17].

Experimentally, several experiments had been performed [20,21], but no evidence of \(\eta\)-mesic nuclei was found. Recently, Sokol et al. [22] claimed that they observed a \(\eta\)-mesic nucleus, \(^{13}\text{C}\), by measuring the invariant mass of correlated \(\pi^-\pi^-\pi^+\) pairs in a photo-mesonic reaction. And more recently, Pfeiffer et al. [23] also claimed they observed some information of an \(\eta\)-mesic nucleus, \(^{\text{\#}}\text{He}\). To get a further understanding on \(\eta\)-mesic nuclei, more studies, both in theory and experiments, are needed.

In our previous work, the \(\eta N\) interaction Lagrangian had been derived from the chiral perturbation theory (ChPT) [24], in which the off-shell term has been related with the \(\eta N\) scattering length by an off-shell term parameter \(c\). Combining this \(\eta N\) Lagrangian with the Lagrangian for nucleons in relativistic mean-field theory (RMF), we have obtained the equations of motion for nucleons and mesons. By solving the these equations self-consistently in RMF, the static properties of \(\eta\)-mesic nuclei, such as the single-particle energy spectra, are gotten. A similar method can be found in the study of kaonic nuclei as well [25,26]. In the RMF calculations, with the existing data of the scattering lengths, the lower limits of the 1s state single-particle \(\eta\) binding energies are \(9 \pm 7\) MeV, and the upper limits are \(70 \pm 10\) MeV. With large scattering length \(a_{\eta N} = 0.75\)–1.05 fm and small imaginary potential \(V_0 \approx 15\) MeV, the discrete bound states of \(^{12}\text{C},^{16}\text{O}\) and \(^{20}\text{Ne}\) may be identified in experiments.

This work is organized as follows. In the subsequent section, the Lagrangian density is given, the equations of motion for nucleons and the meson fields \(\sigma, \omega, \rho, \eta\) are deduced, the imaginary part of the self-energies are introduced. We then present our results and discussions in the third section. Finally a summary is given in the last section.

Framework. –

Lagrangian and equations of motion. In the relativistic mean-field theory, the standard Lagrangian density for an ordinary nucleus can be written as [27,28]

\[
\mathcal{L}_0 = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_A, \tag{1}
\]

where

\[
\mathcal{L}_{\text{Dirac}} = \bar{\Psi}_N (i\gamma^\mu \partial_\mu - M_N) \Psi_N, \tag{2}
\]

\[
\mathcal{L}_\sigma = \frac{1}{2} \partial_\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - g_{\sigma N} \bar{\Psi}_N \sigma \Psi_N - \frac{1}{3} g_{2\sigma} \sigma^2 - \frac{1}{4} g_{3\sigma} \sigma^4, \tag{3}
\]
The scattering length has large uncertainties, which scatters in a large range $a_{NN} = 0.2$–$1.1 \text{ fm}$ [30–34]. Thus, the corresponding value of $\kappa$ is in the range of $(–0.13–0.40) \text{ fm}$. It should be emphasized that in the ChPT the contributions of $N^*(1535)$ cannot be seen directly, however, its contributions are included by the scattering length, which relates to the resonance $N^*(1535)$ directly.

In the mean-field approximation, the meson fields $\sigma$, $\omega$, and $\rho$, and the photons $A_\mu$ are replaced with their mean values, $\langle \sigma \rangle$, $\langle \omega \rangle$, $\langle \rho_\mu \rangle$, and $\langle A_\mu \rangle$, respectively. For a spherical nucleus, only the mean values of the time components $\langle \omega_0 \rangle$, $\langle \rho_0 \rangle$, and $\langle A_0 \rangle$ remain, which are denoted by $\omega_0$, $\rho_0$, and $A_0$, respectively. From the Lagrangian for the $\eta$-nucleus system, the equations of motion for nucleons, $\omega$, $\sigma$, $\rho$, and photons are deduced, which are given by

$$\{ \vec{a} \cdot \vec{F} + \beta [M_N + S(r)] + V(r) \} \psi_N = \mathcal{E} \psi_N,$$

$$\{ -\nabla^2 + m_\eta^2 \} \sigma_0 = -g_{\sigma N} \psi_N \psi_N - g_2 \sigma_0^2 - g_3 \sigma_0^3,$$

$$\{ -\nabla^2 + m_\sigma^2 \} \omega_0 = g_{\omega N} \psi_N \gamma^0 \psi_N,$$

$$\{ -\nabla^2 + m_\rho^2 \} \rho_0 = g_{\rho N} \psi_N \gamma^0 \psi_N,$$

$$-\nabla^2 A_0 = c \psi_N \gamma^0 I_c \psi_N,$$

with

$$S(r) = g_{\sigma N} \sigma_0 - \frac{1}{2} \frac{\Sigma_{\eta N}}{f_\pi^2} \eta^2 - \frac{1}{2} \frac{\kappa}{f_\pi^2} \eta \partial_\mu \eta,$$

$$V(r) = g_{\omega N} \omega_0 + g_{\rho N} \tau_3 \rho_0 + c I_c A_0.$$

In the calculation the spacial terms of the last term in eq. (17) are neglected for a simplicity. And the equation of motion for the $\eta$-meson is derived as

$$[-\nabla^2 + (m_\eta^2 - E^2)] \eta = 0,$$

with

$$\Pi = \frac{1}{f_\pi^2 \left(1 + \frac{\kappa}{f_\pi^2} \eta_\sigma \right)} (\kappa m_\eta^2 + \Sigma_{\eta N}) \eta_s.$$

In the above equations, $\mathcal{E}$ is the nucleon single-particle energy, $E$ is the single-particle energy for the $\eta$-meson, $\eta_\sigma = \psi_N \psi_N$ is the scalar density of nucleons, and $\Pi$ is the self-energy of the $\eta$-meson in the nucleus.

**Imaginary potential.** Within the framework of the RMF model, there is only a real part for the self-energy of the $\eta$-meson in the nucleus. Considering there are strong absorptions for the $\eta$-mesons in a nucleus, in the realistic calculations the imaginary part of the self-energy should be included. Thus, as done in refs. [25,26], we assume a
specific form for the self-energy:

$$\bar{\Pi} = \Pi + i \left[ -2(\text{Re} E) J V_0 \rho \right].$$  \hspace{1cm} (21)

The imaginary part of the potential $\text{Im} U$ adopted is the simple "$tq^2$" form, namely, $\text{Im} U = -f V_0 \theta / \rho \omega$. $f$ is a suppression factor, which will be discussed later. $V_0$ is the imaginary potential depth at normal nuclear density $\rho_0$, which has strong model dependence. The shallowest value of $V_0 \sim 10$ MeV is given by fitting larger scattering length using the "$tq^2$" form [7]. While Waas and Weise studied the s-wave interactions of $\eta$-meson in nuclear medium, and got $V_0 \approx 22$ MeV [3]. Inoue and Oset also obtained $V_0 \approx 29$ MeV with chiral unitary approach [6].

Using the chiral doublet model to incorporate the medium effects of the $N^*(1535)$ resonance, Jido and Nagahiro et al. predicted the largest imaginary potential depth $V_0 \approx 50$ MeV [8,14,19]. Chiang et al. [4] suggested the imaginary potential depth in the range of (12–49) MeV by assuming that the mass of the $N^*(1535)$ did not change in the medium. Thus, in the present work, we set the imaginary potential depth $V_0$ in the range of 10–50 MeV to cover all the possible ranges.

Considering the decay channels should be reduced for the $\eta$-meson being bound in a nucleus, the suppression factor, $f$, is introduced to multiply the imaginary part to decrease the imaginary potentials (widths)$^1$. This method has been used to calculate the width of kaonic nuclei [25,26,35]. There are two main decay channels for $\eta$-mesic nuclei. One is the mesonic decay channel, $\eta N \rightarrow \pi N$. The corresponding suppression factor is given by [25,26,35]

$$f_1 = \frac{M_0^2}{M_{01}^2} \left[ \frac{M_{0}^2 - M_{01}^2}{M_{01}^2 - M_2^2} \right] \Theta(M_1 - M_+),$$  \hspace{1cm} (22)

where $M_{01} = m_\eta + M_N$, $M_+ = m_\pi + M_N$, $M_0 = M_N - m_\eta$, and $M_1 = \text{Re } E + M_N$ is the energy of the bound system $\eta N$. The other channel is the non-mesonic decay channel, $\eta NN \rightarrow NN$, and the corresponding suppression factor is [25,26,35]

$$f_2 = \frac{M_2^2}{M_0^2} \left[ \frac{M_{0}^2 - 4M_0^2}{M_{01}^2 - 4M_0^2} \right] \Theta(M_2 - 2M_0),$$  \hspace{1cm} (23)

where $M_{02} = m_\eta + 2M_N$, $M_2 = \text{Re } E + 2M_N$ correspond to the energies of the free system and the bound system of $\eta NN$, respectively. The mesonic decay and non-mesonic decay are studied in ref. [36], the ratio for the two decay modes are about 90% and 10%, respectively. Thus the suppression factor $f$ can be written as

$$f = 0.9 f_1 + 0.1 f_2.$$  \hspace{1cm} (24)

$^1$ The energy of a free system is larger than the energy of a bound system, thus, for a decay channel its phase space should be suppressed for a bound system. As an example, we can see eq. (22) and eq. (23).

| $V_0 = 15$ | $V_0 = 30$ | $V_0 = 50$ |
|-----------|-----------|-----------|
| $B_{\eta}^{s,p}$ | $B_{\eta}^{s,p}$ | $B_{\eta}^{s,p}$ |
| $\Gamma$ | $\Gamma$ | $\Gamma$ |

Table 2: The single-particle $\eta$ binding energies, $B_{\eta}^{s,p} = m_\eta - \text{Re } E$ and the widths, $\Gamma$, (both in MeV), in various nuclei for $\kappa = -0.13$ fm ($a_{\eta N} = 0.20$ fm), where the complex eigenenergies are, $E = -B_{\eta}^{s,p} + m_\eta - i\Gamma/2$.

| $V_0 = 15$ | $V_0 = 30$ | $V_0 = 50$ |
|-----------|-----------|-----------|
| $B_{\eta}^{s,p}$ | $B_{\eta}^{s,p}$ | $B_{\eta}^{s,p}$ |
| $\Gamma$ | $\Gamma$ | $\Gamma$ |

Table 3: The single-particle $\eta$ binding energies, $B_{\eta}^{s,p} = m_\eta - \text{Re } E$ and the widths, $\Gamma$, (both in MeV), in various nuclei for $\kappa = 0.04$ fm ($a_{\eta N} = 0.50$ fm), where the complex eigenenergies are, $E = -B_{\eta}^{s,p} + m_\eta - i\Gamma/2$.

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Table 4: The single-particle $\eta$ binding energies, $B^{s,p}_\eta=m_\eta-\text{Re }E$ and the widths, $\Gamma$, (both in MeV), in various nuclei for $\kappa=0.19$ fm ($a^{NN}=0.75$ fm) and $\kappa=0.40$ fm ($a^{NN}=1.05$ fm), where the complex eigenenergies are, $E=-B^{s,p}_\eta+m_\eta-i\Gamma/2$.

| $V_0=15$ | $V_0=30$ | $V_0=50$ |
|----------|----------|----------|
| $B^{s,p}_\eta$ | $B^{s,p}_\eta$ | $B^{s,p}_\eta$ |
| $\kappa=0.19$ fm ($a^{NN}=0.75$ fm) | $\kappa=0.40$ fm ($a^{NN}=1.05$ fm) |
| $^{12}$C $\eta$ | $^{16}$O $\eta$ | $^{20}$Ne $\eta$ |
| $1s$ | $46.2$ | $43.2$ | $46.3$ | $69.8$ | $65.4$ | $69.1$ |
| $1p$ | $6.6$ | $3.2$ | $18.6$ | $23.4$ | $31.1$ | $37.8$ |
| $^{24}$Mg $\eta$ | $^{28}$Si $\eta$ | $^{32}$S $\eta$ |
| $1s$ | $50.9$ | $55.1$ | $57.4$ | $74.7$ | $79.7$ | $82.9$ |
| $1p$ | $25.2$ | $31.0$ | $30.9$ | $46.0$ | $53.1$ | $52.8$ |
| $^{36}$Ar $\eta$ | $^{40}$Ca $\eta$ | $^{44}$Ti $\eta$ |
| $1s$ | $56.2$ | $55.4$ | $56.3$ | $81.2$ | $79.8$ | $80.7$ |
| $1p$ | $32.5$ | $34.3$ | $36.8$ | $54.3$ | $56.2$ | $59.0$ |

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**Single-particle $\eta$ binding energy and width.** Then the modified Klein-Gordon equation can be expressed as

$$[\mathbf{-\nabla}^2 + (m_\eta^2 - E^2) + \Pi] \eta = 0.$$  (25)

The complex eigenenergy is

$$E = -B^{s,p}_\eta + m_\eta - i\Gamma/2,$$  (26)

where the real part corresponds to the single-particle $\eta$ binding energy, which is defined as

$$B^{s,p}_\eta = m_\eta - \text{Re }E,$$  (27)

and the imaginary part of the complex eigenenergy corresponds to the width

$$\Gamma = -2\text{Im }E.$$  (28)

Solving eqs. (12)–(16) and eq. (25) self-consistently, we can obtain the single-particle energy spectra and widths of $\eta$-mesic nuclei.

**Results and discussions.** In this section, the single-particle energy spectra and the widths of the possible $\eta$-mesic nuclei, such as $^{12}$C, $^{16}$O, $^{20}$Ne, $^{24}$Mg, $^{28}$Si, $^{32}$S, $^{36}$Ar, $^{40}$Ca and $^{44}$Ti are calculated in the RMF. For the uncertainties of the parameter $\kappa$ (i.e. the scattering length $a^{NN}$), which give large uncertainties for the $\eta$ nuclear potentials, we choose four values of $\kappa$ ($0.13, 0.04, 0.19$ and $0.40$ fm corresponding to $a^{NN}=0.20, 0.50, 0.75, 1.05$ fm) to cover all the possible scattering lengths. In each case, we also suppose $V_0=15$, $30$ and $50$ MeV, respectively, which can cover all the possible ranges of the imaginary potential. The results, including the single-particle $\eta$ binding energies ($B^{s,p}_\eta$) and the widths ($\Gamma$), for $\kappa=-0.13$ fm ($a^{NN}=0.20$ fm) and $\kappa=0.04$ fm ($a^{NN}=0.50$ fm) are shown in tables 2 and 3, respectively. And the results for $\kappa=0.19, 0.40$ fm ($a^{NN}=0.75, 1.05$ fm) are listed in table 4.

For $a^{NN}=0.20$ fm (see table 2), it is found that the imaginary potential depth $V_0$ has effects on the lighter nuclei to form $\eta$ quasi-bound states. For example, with $V_0=15$ MeV, quasi-bound states can be found with nucleon number $A \geq 20$, however, they are only found in...
the $A \geq 36$ nuclei with $V_0 = 50$ MeV. The 1s state single-particle binding energies are $(9 \pm 7)$ MeV, increasing with the nucleon number. The widths are much larger than the single-particle binding energies even we use the smallest $V_0 = 15$ MeV. Thus, no $\eta$-mesic nuclei can be observed in experiments.

For $a^{\eta N} = 0.50$ fm (see table 3) the ground-state single-particle binding energies are $(26 \pm 10)$ MeV. If the imaginary part $V_0 = 15$ MeV, the decay widths are comparable with the binding energies, thus, in this case the $\eta$-mesic nuclei may be observed in the light nuclei when $a^{\eta N} > 0.50$ fm. On the contrary, when $a^{\eta N} < 0.50$ fm, no $\eta$-mesic nuclei can be observed in experiments.

For $a^{\eta N} = (0.75 \pm 1.05)$ fm (see table 4), the 1s state single-particle binding energies are in the range of $(48 \pm 10 \pm 70 \pm 10)$ MeV, and those of 1p states are in the region of $(15 \pm 12 - 38 \pm 21)$ MeV, increasing monotonically with the nucleon number $A$. The separations of the single-particle $\eta$ binding energies between the 1p and 1s states are on the magnitude of $(30 \pm 10 \pm 35 \pm 13)$ MeV, decreasing with the increase of the nucleon number in general. When $V_0 \sim 15$ MeV, the sum of the half-widths of the 1s and 1p states are narrower than the separations of the single-particle $\eta$ binding energies between 1s and 1p states for $C$, $O$, $Ne$, which implies that some discrete states should be identified in experiments for these nuclei. However, if $V_0 > 30$ MeV no $\eta$-mesic nuclei could be observed in experiments according to our calculations.

From tables 3 and 4, it is found that the widths of the 1s states are in the ranges of $(28 \pm 7 - 104 \pm 14)$ MeV and those of 1p states are $(26 \pm 3 - 89 \pm 7)$ MeV, respectively, for $V_0 = (15 - 50)$ MeV. The imaginary potential depth $V_0$ has slight effects on the values of the single-particle energy $E_{1\eta}^{s,p}$, the effects decrease with the increment of $V_0$. For example, if we change $V_0$ from 15 MeV to 50 MeV, the single-particle energies decrease about $(3 - 8)$ MeV for both 1s and 1p states.

Summary. – Some possible $\eta$-mesic nuclei from $^{12}$C to $^{44}$Ti have been studied in the RMF. The $\eta$ single-particle energy is sensitive to the $\eta N$ scattering length (i.e. “off-shell” term parameter $\kappa$). In the whole possible range for the scattering length, the lower limits of the 1s state single-particle $\eta$ binding energies are $(9 \pm 7)$ MeV, and the upper limits are $(70 \pm 10)$ MeV. The widths of 1s states are in the ranges of $(28 \pm 7 - 104 \pm 14)$ MeV and those of 1p states are $(26 \pm 3 - 89 \pm 7)$ MeV.

When the scattering length $a^{\eta N} = (0.75 \pm 1.05)$ fm, and the imaginary potential $V_0 \leq 15$ MeV, the sum of the half-widths of the 1s and 1p states for $^{12}$C, $^{16}$O and $^{20}$Ne are smaller than the separations of the single-particle binding energies between the two low-lying states of these $\eta$-mesic nuclei, which implies that discrete $\eta$-meson bound states may be identified in experiments in these nuclei. However, when the scattering length $a^{\eta N} < 0.5$ fm, or the imaginary potential $V_0 > 30$ MeV, no discrete $\eta$-meson bound states could be identified in experiments.

Finally, we should point out that it is an attempt to study the $\eta$-mesic nuclei with the $\eta N$ interaction deduced from ChPT. In our method the contributions of resonances, such as $N^*(1535)$, are only included indirectly by the $\eta N$ scattering length, which relates to the resonances directly. The imaginary potential is phenomenologically introduced in this paper, which has a large uncertainty. Thus, more realistic $\eta N$ interaction which introduces the resonances naturally, and more fundamental imaginary potential should be pursued in the future work.

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REFERENCES

[1] Haider Q. and Liu L. C., Phys. Lett. B, 172 (1986) 257; Liu L. C. and Haider Q., Phys. Rev. C, 34 (1986) 1845.
[2] Li G. L., Cheung W. K. and Kuo T. T., Phys. Lett. B, 195 (1987) 515.
[3] Waas T. and Weise W., Nucl. Phys. A, 625 (1997) 287.
[4] Chiang H. C., Oset E. and Liu L. C., Phys. Rev. C, 44 (1991) 738.
[5] Tsushima K., Lu D. H., Thomas A. W. and Saito K., Phys. Lett. B, 443 (1998) 20.
[6] Inoue T. and Oset E., Nucl. Phys. A, 710 (2002) 354.
[7] García-Reco C., Inoue T., Nieves J. and Oset E., Phys. Lett. B, 550 (2002) 47.
[8] Nagahiro H., Jido D. and Hirenzaki S., Phys. Rev. C, 68 (2003) 035205.
[9] Shirotsev A., Haidenbauer J., Niskanen J. A. and Meißner Ulf-G., Phys. Rev. C, 70 (2004) 047001.
[10] Wycech S., Green A. M. and Niskanen J. A., Phys. Rev. C, 52 (1995) 544.
[11] Johnson J. D. et al., Phys. Rev. C, 47 (1993) 2571.
[12] Raktyansky S. A., Sofianos S. A., Braun M., Belyaev V. B. and Sandhas W., Phys. Rev. C, 53 (1996) R2043.
[13] Haider Q. and Liu L. C., Phys. Rev. C, 66 (2002) 045208.
[14] Jido D., Nagahiro H. and Hirenzaki S., Phys. Rev. C, 66 (2002) 045202.
[15] Batinic M. et al., Phys. Rev. C, 57 (1998) 1004.
[16] Green A. M. and Wycech S., Phys. Rev. C, 55 (1997) R2167.
[17] Kulpa J., Wycech S. and Green A. M., e-preprint nucl-th/9807020.
[18] Hayano R. S., Hirenzaki S. and Gilitzer A., Eur. Phys. J. A, 6 (1999) 105.
[19] Nagahiro H. et al., Nucl. Phys. A, 761 (2005) 92.
[20] Chrien R. E. et al., Phys. Rev. Lett., 60 (1988) 2595.
[21] Johnson J. D. et al., Phys. Rev. C, 47 (1993) 2571.
[22] Sokol G. A. and Pavlyuchenko L. N., nucl-ex/0111020.
[23] Pfeiffer M. and Ahrens J. et al., Phys. Rev. Lett., 92 (2004) 232001.
[24] Zhong X. H. et al., Phys. Rev. C, 73 (2006) 015205.
[25] Zhong X. H. et al., Phys. Rev. C, 74 (2006) 034321.
[26] Mareš J., Friedman E. and Gal A., Phys. Lett. B, 606 (2005) 295.
[27] Serot B. D. and Walecka J. D., Adv. Nucl. Phys., 16 (1986) 1.
[28] Reinhard P.-G., Rep. Prog. Phys., 52 (1989) 439.
[29] Sharma M. M. and Nagaragian M. A., Phys. Lett. B, 312 (1993) 377.
[30] Green A. M. and Wycech S., Phys. Rev. C, 71 (2005) 014001.
[31] Renard F. et al., Phys. Lett. B, 528 (2002) 215.
[32] Arndt R. A., Briscoe W. J., Morrison T. W., Strakovsky I. I., Workman R. L. and Gridnev A. B., Phys. Rev. C, 72 (2005) 045202.
[33] Kaiser N., Waas T. and Weise W., Nucl. Phys. A, 612 (1997) 297.
[34] Niskanen J. A., Int. J. Mod. Phys. A, 20 (2005) 634.
[35] Mares J., Friedman E. and Gal A., Nucl. Phys. A, 770 (2006) 84.
[36] Anikina M. Kh. and Anisimov Yu. S. et al., nucl-ex/0412036.