Magnetic layer in neutron wave resonator

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Abstract

Expressions for the neutron density and the neutron reflection amplitude are given in the case of a non-collinear magnetic layer inside of the neutron wave resonator subject to a static or a rotating magnetic fields. It is shown that the enhancement of the spin-flip reflection intensity and density of neutrons in opposite to initial spin state are enhanced in second and third degree relatively of enhancement of neutron density in the initial spin state, correspondently. Conditions are defined for high sensitive measurements of the magnetic layer parameters.

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1. Introduction

A layered neutron resonator structure (neutron wave resonator (NWR)) is a three-layered structure (Fig. 1) in which the top (1) and bottom layers (3) have a higher neutron-matter interaction potential with respect to the middle layer (2).

Due to the multiple neutron reflections in the NWR, the neutron density increases and that reflects in an increase of scattering and the emission of radiation, which appears at neutron absorption [1]. NWR can thus be used to increase the sensitivity of neutron scattering and absorption and spin-flip measurements [2]. For magnetic NWR, in which the magnetic induction vector of the layer placed in the second layer (2) is non-collinear with respect to the neutron polarization vector, a strong increase of the spin-flip probability is

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observed [3-6]. In this communication, the spin-flip processes in static and rotating fields are considered in
details and compared with the non spin-flip processes.

Fig. 1. Scheme of neutron wave resonator: 1 - amplifying layer, 2 - phase-shifting layer, 3 - reflecting layer, 4 - investigated
magnetic layer, 5 - scatters.

2. Non-magnetic NWR

Let us consider the neutrons incident on the NWR in Z-direction (point z=0 corresponds to the interface “(2)-(3)”). In the phase-shifting layer (2), the neutron density $|\psi|^2$, is increased by the coefficient $N$:

$$N = \frac{1}{1 - r_1 r_3 \exp(-2k_2L_2)}$$

(1)

where $r_1$ and $t_1$ - reflection and transmission amplitude for amplifying layer (1), correspondently, $r_3$ - reflection amplitude for the reflecting layer (3), $k_2$ - perpendicular component of the neutron wave vector in phase-shifting layer, $L_2$ - thickness of phase-shifting layer.

At the resonance, $\varphi_l + \varphi_r + 2k_2L_2 = 2\pi n$, where $k_2$ is the real part of wave vector, $\varphi_l$ and $\varphi_r$ are phases of complex reflection amplitude $r_1$ and $r_3$, respectively. Using the condition $|t_1|^2 = 1 - |r_1|^2$ (neutron absorption is absents in the amplifying layer), the $N$ reduces to:

$$N = \frac{1}{1 - r_1 \exp(-2k_2L_2)}$$

(2)

where $k_2$ is imaginary part of perpendicular component of wave vector in phase-shifting layer.

In the total neutron reflection regime without of neutron absorption in reflecting layer ($|r_3| = 1$), small neutron absorption in phase-shifting layer ($2k_2L_2 << 1$) and $|r_1| \approx 1$ the Eq. (2) transforms to the simple form:

$$N = \frac{1}{1 - r_1 \exp(-2k_2L_2)}$$

(3)

It is seen that $N > 1$ and can be very large in case of $|r_1| \to 1$ and absence of neutron absorption in amplifying layer ($k_{21} = 0$). In the case we have for neutron absorption coefficient $M = 1 - |r|^2$ [5], where $r$ is
neutron reflection amplitude for resonator structure:

\[ M = 4k_1^2 L_2 (1 + |r_1|) \left/ \left( (1 - |r_1| \exp(-2k_1 L_2)) \right) \right] \]  

(4)

From (4) it follows for enhancement coefficient of neutron absorption

\[ \eta_M = \frac{M}{M_{(r_1=0)}} = \frac{(1 + |r_1|) \left/ \left( (1 - |r_1| \exp(-2k_1 L_2)) \right) \right]} \]  

(5)

By comparing Eq. (2) and (5) it can be seen that the enhancement coefficient of neutron density is equal to enhancement coefficient of neutron absorption or \( \eta_N = \eta_M \).

Fig. 2. Dependences of neutron density \( N \) (curves 1-4) and neutron absorption coefficient \( M \) (curves 5-8) on perpendicular component of wave vector in vacuum \( k(\text{Å}^{-1}) \) for structure \( \text{Be}(L_1)\text{Al}(L_2=80\text{nm})\text{Be} \) at different values of \( L_1 \): 0 – curves 1 and 5, 10 nm – curves 2 and 6, 20 nm – curves 3 and 7, 30 nm – curves 4 and 8.

Figure 2 shows the results of calculation of the functions \( N(k) \) and \( M(k) \) for the structure \( \text{Be}(L_1)\text{Al}(L_2=80\text{nm})\text{Be} \) for \( L_1 = 0, 10, 20 \) and 30 nm. It is seen that with increasing \( L_1 \) (proportionally increasing \( |r_1| \)) the neutron density and the neutron absorption coefficient grow at the resonance values of the wave vector \( k(n=1)=0.00603\text{Å}^{-1} \) and \( k(n=2)=0.00802\text{Å}^{-1} \). At the same time, the enhancement coefficient \( \eta_N(L_1=30\text{nm}) \) is 254.9 and 87.8 at resonance for the first \( (n=1) \) and second \( (n=2) \) orders, respectively. In turn, the absorption enhancement coefficient \( \eta_M(L_1=30\text{nm}) \) is 255.3 and 88.0 in the first and the second resonances, respectively. It is seen that the equality \( \eta_N = \eta_M \) holds quite well. A little larger \( \eta_M \) than \( \eta_N \) is due to neutron absorption in the first beryllium layer for \( L_1=30 \) nm. It should be remembered that we obtained \( \eta_N = \eta_M \) under assumption that neutrons are not absorbed in the first and the second layer, i.e., the imaginary part of the potential of these layers was set to zero.
3. NWR in a static magnetic field

Consider the textbook case of a magnetic NWR where the first layer is non-magnetic, the second layer of thickness $L$ is vacuum and third layer is half-space with a magnetic induction vector $B$ which is non-collinear with respect to the external magnetic field $H$. The field $H$ defines the quantification axis of the neutron spins. In this case, the enhancement coefficient of the spin-flip reflection coefficient $R_{sf} = k_f r_{sf}^2 / k_i$ where $k_i$ and $k_f$ are initial and final neutron wave vectors is given by:

$$R_{sf} = \frac{|t_1|^2}{(1 - \exp(2ik_2L_2) r_1 r^\ast)(1 - \exp(2i k_2 L_2 ) r_1 r^\ast)}$$  \hspace{1cm} (6)

Now the important question is the difference between the resonance wave vectors $\Delta k = k^- - k^+$ and the widths of the resonances $\Delta k^-$ and $\Delta k^+$. If $(\alpha U_{3R}, k^2) \gg \beta B$, where $\alpha = 2m/\hbar^2$, $\beta = \mu a$, $m$ is mass and $\mu$ is magnetic moment of neutron, for the resonance of the first order ($n = 1$) we have:

$$\Delta k = 2\beta B/(\alpha U_{3R})^{1/2} / \pi$$  \hspace{1cm} (7)

For the half-width of resonances we have

$$\Delta k^- = (1 - |r_1|)/(2L_2|r_1 r^\ast|^{1/2}\exp(-k_2L_2)), \quad \Delta k^+ = (1 - |r_1 r^\ast|)/(2L_2|r_1 r^+|^{1/2}\exp(-k_2L_2))$$  \hspace{1cm} (8)

At total reflection regime ($|r_1| = |r_1| = 1$) and $|r_1| \approx 1$, the half-width of the different resonances are equal:

$$\Delta k^- = \Delta k^+ = \Delta k = (1 - |r_1|)/(2L_2|r_1|^{1/2}\exp(-k_2L_2))$$  \hspace{1cm} (9)

In case of overlapping resonances ($\Delta k \leq (\Delta k^+ + \Delta k^-)$), it follows the relation

$$B \leq (\alpha U_{3R})^{1/2}(k/\beta)(1 - |r_1|)/(2|r_1|^{1/2}\exp(-k_2L_2))$$  \hspace{1cm} (10)

At condition (9) we have for enhancement of the spin-flip reflection coefficient

$$\eta_{Rsf} \approx (1 - |r_1|^2)/(1 - |r_1|^4) = (1 + |r_1|^2)/(1 - |r_1|^2)$$  \hspace{1cm} (11)

Comparing (11) with (3) and (5) we get at $k_2 = 0$ the relation:

$$\eta_{Rsf,j} = \frac{\eta_M^2}{\eta_N} = \eta_N^2$$  \hspace{1cm} (12)

Consider the neutron density spin-flip enhancement $\eta_{Nsf}$ for neutrons which propagate in the second layer (2). The $\eta_{Nsf}$ can be defined at the detection of the scattering intensity $J_{sf}$ (fig. 1), for instance, at scattering of neutrons on clusters situated in the second layer. It follows for $\eta_{Nsf}$

$$\eta_{Nsf} = \eta_{Rsf,j} / t_1^2 = (1 - |r_1|^2)/(1 - |r_1|^4) = (1 + |r_1|^2)/(1 - |r_1|^2) \approx \eta_N^3/(1 + |r_1|^2)$$  \hspace{1cm} (13)
It is seen, that spin-flip enhancement $\eta_{\text{nsf}}$ is proportional to the third power of $\eta_N$. At that time at absence of resonance overlap the $\eta_{\text{nsf}}$ is equal to $\eta_N$. In fig. 3 the dependences $N_{\text{nsf}}(k)$, $N_{\text{sf}}(k)$, $R_{\text{sf}}(k)$ and $M(k)$ for $Be(L_1)/Al(L_2 = 80 \text{nm})/Fe(J_x=10^{-5}\text{T})$ at values $L_1=0$ and 30 nm are presented. For resonance of first order, the enhancement coefficients are $\eta_{\text{nsf}}=247.96$, $\eta_{\text{nsf}}=248.28=1.0013\eta_{\text{nsf}}$, $\eta_{\text{nsf}}=61484=1.0011N_{\text{nsf}}^2$, $\eta_{\text{nsf}}=448719=\eta_{\text{nsf}}^3/3.4$. It is seen that relations (12) and (13) hold well.

Note in the case of magnetic field $H$ the difference $\Delta k$ can be decreased because of compensation of neutron precession phases. For that the next relation follows at magnetic reflecting layer

\[ H \approx B/(L_2 (\alpha U_{3R})^{1/2}) \]  

(14)

Now let us consider the structure (fig.1), which is formed by non-magnetic NWR with a magnetic thin layer placed inside of NWR second layer (2). We will not repeat the all transformation procedure of expressions and we only present the final formula for spin-flip reflection amplitude at condition $(r_{22^+}, r_{22^-}) \ll (t_{22^+}, t_{22^-})$:

\[ r_{sf} = 2b_t t_{22^+} t_{22^-} r_3 \exp(2ik(L_{21}+L_{23}))/\left\{[1- r_1 r_3 \exp(2ik(L_{21}+L_{23}))(t_{22}(B))^2 \times \right\} \\
[1- r_1 r_3 \exp(2ik(L_{21}+L_{23}))(t_{22}(-B))^2 \} \} \]  

(15)

where $t_{22}(\pm B) = e(\pm B)[(1-r^2(\pm B))/(1-r(\pm B)e^2(\pm B))]$, $e(\pm B) \equiv \exp(ik_5(\pm B)L_3)$, $r(\pm B) = (k-k(\pm B))/(k+k(\pm B))$, $k(\pm B) = (k^2-\alpha U_{2Rx}(\pm BB))^{1/2}$.

We see in this case the resonance pairs of neutron wave vector have place also. Further at conditions of thin magnetic layer and small magnetic induction it follows for $\Delta k$
$$\Delta k = 2 \beta BL_{22}\left[(k^2 - \alpha U_{22R})^{1/2} x(kL_{22}/(k^2 - \alpha U_{22R}))^{1/2} + k(L_{21} + L_{23})/(k^2 - \alpha U_{21R})^{1/2}\right]$$  \hspace{1cm} (16)

It follows for $k^2 > \alpha U_{22R}$ and at the first resonance order ($kx(L_{21} + L_{22} + L_{23}) \approx \pi$)

$$\Delta k \approx 2 \beta BL_{22}/\pi$$  \hspace{1cm} (17)

It is seen from (17) that if the magnetic layer is thin, the magnetic induction can be big and that does not lead to splitting of the peaks. In case of magnetic field $H$ in non-magnetic layers with thickness $L_{21}$ and $L_{22}$, Eq. (16) transforms into

$$\Delta k = 2(\beta kL_{22})\left[(B_xL_{22} + H_x(L_{21} + L_{23}))^2 + [B_yL_{22} + H_y(L_{21} + L_{23})]^2\right]^{1/2}$$  \hspace{1cm} (18)

For $k^2 > \alpha U_{22R} \geq \alpha U_{21R} (U_{23R})$

So it is seen from Eq. (18) that $\Delta k$ goes to minimal value at next condition

$$H_x(L_{21} + L_{23}) = -B_yL_{22}$$  \hspace{1cm} (19)

In Fig. 4 the dependences $R_{sf}(k)$ for cases of separate Co layer and Co layer placed in resonator structure are presented.

As follows the minimal level $R_{sf} = 10^{-7}$ is obtained at $fB_x = 10^{-10} \text{A}^{-2}$ and a thickness of the magnetic layer of 1nm. Further at resonance value $k = 4.44 \times 10^3 \text{A}^{-1}$ the enhancement coefficients are $\eta_{ref} = 1.6 \times 10^7 = 1.6 \eta_{nsf}^2$, $\eta_{ref} = 1.27 \times 10^7 = 0.65 \eta_{nsf}^3$ and $\eta_{nsf} = 270$.

In Fig. 5 the dependences $R_{sf}(k)$ for cases of the magnetic field $H=0$ (curve 1) and $H= -0.45 \text{kOe}$ (curve 2) are
presented. Magnetic field $H= -0.45$ kOe compensates the acting of the layer magnetic induction $1.045$T and reflectivity dependence $R_{sf}(k)$ becomes with one peak for each order.

![Graph](image-url)

Fig. 5. Dependence $R_{sf}$ on perpendicular component of wave vector in vacuum $k$(Å⁻¹) for structure $-Be(30\text{nm})/Al(57\text{nm})/Co(3\text{nm}, J_z=1\text{T}, J_x=10^{-2}\text{T})/Al(20\text{nm})/Be$: curve 1 - $H=0$, curve 2 - $H=0.45$ kOe.

4. NWR in static and rotating magnetic fields

The neutron interaction with a rotating magnetic field (RMF) was described by Rabi [7, 8]. For the spin flip probability of a particle which is characterized by a gyromagnetic factor $\gamma$, one has the following relation:

$$P = \left( \frac{\alpha_0^2}{\left( \alpha_0^2 + (\omega_0 - \omega)^2 \right)^2} \right) \sin^2 \left( \frac{\alpha_0^2}{2} \left( \omega_0 - \omega \right) \right) \frac{1}{2} \right.$$  \hspace{1cm} (20)

where $\omega_0 = \gamma B_0$, $\omega = \gamma B$. Further the RMF and oscillating magnetic field (OMF) was used for neutron beam formation and definition of neutron spin parameters [9-17]. We consider a task of application the OMF for multilayer investigations. Difficulties of application of OMF are connected with small thickness a multilayer structure. For example, at RMF amplitude $10$ Oe, perpendicular component of neutron velocity $10$ m/s, the spin flip probability is $P \approx 10^{-10}$ for a layer thickness of $1$nm. Our investigations show [18-20] an application of OMF allows to do absolute measurements of magnetic induction for micrometer layers, to specify and define spatial profile of static and oscillating magnetic permeability in nanometer layers, to define the oscillating magnetic permeability in layers of angstrom thickness.

Minimal difference $\Delta k$ in the case is realized at next condition [6]

$$(U_{1b} - U_{1a}) (L_{21} + L_{22}) + (U_{1b} - U_{1a}) L_{22} = 0,$$  \hspace{1cm} (21)

where $U_{1b} = \mu H$, $U_{1a} = \mu B$, $U_{a} = h \omega$. 

Fig. 6. Dependence $G_{sf}(k)=|r_{sf}|^2$ on perpendicular component of wave vector in vacuum $k(\text{Å}^{-1})$ (is normalized on critical copper wave vector $k_{Cu}=9.1\times10^3$ Å$^{-1}$) for structure Cu/Al(15nm)/Co(0.1nm)/Al(15nm)/Cu(70nm) for $U_{H1}=3\times10^3 U_{Cu}$, $U_{H1}=1.15\times10^5 U_{Cu}$, $U_{a}=3\times10^3 U_{Cu}$ and values $U_{H1}-U_{a}$ and $U_{H1}-U_{a}$: $U_{B1}-U_{a}=3\times10^2 U_{Cu}$ and $U_{H1}-U_{a}=0$ (curve 1); $U_{B1}-U_{a}=0$ and $U_{H1}-U_{a}=0.9\times10^4 U_{Cu}$ (curve 2); $U_{B1}-U_{a}=3\times10^2 U_{Cu}$ and $U_{H1}-U_{a}=0.9\times10^4 U_{Cu}$ (curve 3); $U_{B1}-U_{a}=3\times10^3 U_{Cu}$ and $U_{H1}-U_{a}=-0.9\times10^4 U_{Cu}$ (curve 4); $U_{B1}-U_{a}=-3\times10^2 U_{Cu}$ and $U_{H1}-U_{a}=0.9\times10^4 U_{Cu}$ (curve 5).

In Fig. 6 is presented the neutron spin flip reflectivity $R_{sf}(k)$ at $U_{B1}=3\times10^3$, $U_{H1}=1.15\times10^5$, $U_{a}=3\times10^4$ and different values and signs of differences $U_{B1}-U_{a}$ and $U_{H1}-U_{a}$. The 1 and 2 curves have the same maximal value and correspond to $U_{B1}-U_{a}=3\times10^2 U_{Cu}$, $U_{H1}-U_{a}=0$ and $U_{B1}-U_{a}=0$, $U_{H1}-U_{a}=0.9\times10^4 U_{Cu}$. At that the $U_{B1}-U_{a}$ (curve 1)/$U_{H1}-U_{a}$ (curve 2)=330. For curve 3 the $U_{B1}-U_{a}=3\times10^2 U_{Cu}>0$ and $U_{H1}-U_{a}=0.9\times10^4 U_{Cu}>0$ and we see increasing of distance between peaks. For curve 4 the $U_{B1}-U_{a}=3\times10^2 U_{Cu}>0$ and $U_{H1}-U_{a}=-0.9\times10^4 U_{Cu}<0$ and for curve 5 the $U_{B1}-U_{a}=-3\times10^2 U_{Cu}<0$ and $U_{H1}-U_{a}=0.9\times10^4 U_{Cu}>0$. There $U_{Cu}=172$ neV is nuclear potential of copper. We see at the different signs $U_{B1}-U_{a}$ and $U_{H1}-U_{a}$ the curves 4 and 5 have one maximum. Such behavior of the $G_{sf}(k)$ is connected with realization of the Eq. (21).

5. Estimations
We now estimate a minimal value $B_{1\text{min}}$ (or $B_{1\text{max}}$). Measurable spin-flip reflectivity $R_{sf}$ of separate sample (without of neutron wave resonator) is limited by the spectrometer resolution $\varepsilon=\delta \lambda/k$ and polarization ratio $\chi$.

In the spin-flip reflection channel we have a neutron count:

$$N=W(\eta_{Nsf}^2 R_{sf}+(1-\eta_{Nsf}^2 R_{sf})/\chi),$$

(22)

where $W=J_0 S t 2 \delta \lambda \delta \Omega$, $J_0$ is flux before of sample, $S$ is square of sample cross-section, $t$ is the measurement time, $\delta \lambda$ is rms of the wavelength deviation, $\delta \Omega$ is rms of solid angle of neutron source visibility. Use the relations $\delta \lambda/\lambda=\delta \theta/\Omega=\pi/\eta_{Nsf}$ [21] and $\eta_{Nsf}^2 R_{sf}<1$ the Eq. (22) transforms to next
\[ N = F(R_{sf} + 1/(\eta_{nsf}^2 \chi)) \]  

(23)

where \( F = 82 J_0 \theta_0 \delta \theta \).

There are two cases for magnitude of the statistical error \( \Delta R_{sf} \). For first case at \( R_{sf} > 1/(\eta_{nsf}^2 \chi) \) it follows

\[ (\chi F)^{-1/2} \eta_{nsf}^{-1} < \Delta R_{sf} = (R_{sf}/F)^{1/2} < F^{-1/2} \eta_{nsf}^{-1} \]  

(24)

For the opposite case at \( R_{sf} < 1/(\eta_{nsf}^2 \chi) \) we have

\[ \Delta R_{sf} = (2/(\chi F))^{1/2} \eta_{nsf}^{-1} \]  

(25)

From Eq. (24-25) it is seen the minimal value of \( R_{sf} \) is proportional to the inverse magnitude of enhancement \( \eta_{nsf}^{-1} \). For typical values of the \( S = 0.03 \text{cm}^2, \chi = 20, t = 10^5 \text{s}(1 \text{day}), J_0 = 10^{12} \text{n/sec/cm}^2/\text{strad} \) (reactor IBR-2 in Dubna, Russia), \( \eta_{nsf} = 100(\varepsilon = 3 \times 10^{-3}), \lambda = 3 \text{Å}, \theta = 3 \text{mrad}, \delta \theta = 10^2 \) we have \( F = 2.4 \times 10^{13} \) and it corresponds \( \Delta R_{sf} = 6.5 \times 10^{-10} \) for \( R_{sf} < 5 \times 10^{-6} \). The relation \( \Delta R_{sf}/R_{sf} = 1 \) corresponds the magnetic induction \( B_{l_{min}}(B_{1_{min}}) = 7 \text{Gs of layer with thickness 1nm} \). For maximal value \( \eta_{nsf} = 4 \times 10^4 \) the wavelength resolution must be \( \varepsilon = 10^{-5} \) and it gives the \( \Delta R_{sf} = 1.6 \times 10^{-12} \). It corresponds the \( B_{l_{min}}(B_{1_{min}}) = 0.35 \text{Gs at \Delta R_{sf}/R_{sf}=1}. \)

At second method of measurement when exists the angle splitting [22] of the spin-flip \( I_{sf} \) and non spin-flip \( I_{nsf} \) of neutron fluxes (look the Fig.1) we have \( N = FR_{sf} \) what corresponds the \( \Delta R_{sf} = (R_{sf}/F)^{1/2} \). This relation is the same as relation (24) but is fulfilled now for any value of \( R_{sf} \). At condition \( \Delta R_{sf}/R_{sf} = 1 \) we have \( R_{sf} = F^{-1} \), what at the above denoted other parameter values gives the \( R_{sf} = 4.2 \times 10^{-14} \) ( \( B_{l_{min}}(B_{1_{min}}) = 0.06 \text{Gs for layer with thickness 1nm} \)).

Now let us consider a third method registration of neutrons when after coherent spin-flip and non spin-flip processes neutrons are scattered in the inhomogeneous phase-shifting layer. For spin-flip scattered neutron count we have in case of angle splitting

\[ N_{sc, sf} = AW \eta_{nsf}^3 R_{sf} \]  

(26)

where \( A \) is scattering probability. Because increasing of \( A \) reflects in decreasing of \( \eta_{nsf} \) there is question in magnitude of \( A \) for minimal \( \Delta R_{sf} \). Really for maximal \( N_{sc, sf} \) a magnitude of \( A \) is limited by value \( \eta_{nsf}^{-1} \). As result we get the same as at second registration method \( \Delta R_{sf} = (R_{sf}/F)^{1/2} \).

6. Conclusion

We have shown in the NWR the spin-flip signal can be enhanced due to overlap of resonances in second or third degree relatively to enhancement of neutron absorption or non spin-flip density. The measurements with neutron wave resonator allow to define in \( \eta_{nsf} \) a smaller value of \( R_{sf} \) and in \( \eta_{nsf}^2 \) larger a ratio of spin-flip intensity to background one. As result you can conduct neutron measurements with weakly magnetized non-collinear thin magnetic layers.

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References
[1] Aksenov V.L., Nikitenko Yu.V., Radu F., Gledenov Yu.M., Sedyshev P.V. Physica B 2000;276-278:946-7.
[2] Aksenov V.L., Nikitenko Yu.V. Physica B 2001;297:101-112.
[3] Aksenov V.L., Nikitenko Yu.V. Neutron News 2005; 16 (3):19 - 23.
[4] Aksenov V.L., Ignatovich V.K., Nikitenko Yu.V. Crystallography Reports 2006, 51(5):734-753.
[5] Khaidukov Yu. N., Nikitenko Yu.V. NIM A 2011; 629:245
[6] Nikitenko Yu.V., Journal of Surface Investigation, 2012; 10: 1-13.
[7] Rabi I. I. Phys. Rev. 1937; 51: 652.
[8] Rabi I. I., Ramsey N.F., Schwinger J. Reviews of Modern Physics. 1954; 26:167.
[9] Alvarez L.W., Bloch F. Phys. Rev. 1940; 57:111.
[10] Stanford C.P. et al. Phys. Rev. 1954; 94:374.
[11] Drabkin G.M. JETP 1962;43:1107.
[12] Drabkin G.M., Zhitnikov P.A. JETP 1960;38:1013.
[13] Kruger E. Nucleonica 1980;25:889-893.
[14] Gehler R., Golub R. Z. Phys. B 1987;65:269.
[15] Frank A.I., Nosov V.G., Nuclear Physics 1994;57:1029.
[16] Felber J., Gehler R., Golub R. et al. Found. Phys. 1999;29:381.
[17] Kozlov A.V., Frank A.I. Nuclear Physics 2005;68:1149-1164.
[18] Ignatovich V. K., Nikitenko Yu.V., Radu F. NIM A 2009;604:653.
[19] Nikitenko Yu.V., Ignatovich V. K., Radu F. Physica B 2011;406:2473.
[20] Ignatovich V. K., Nikitenko Yu.V., Radu F. NIM A 2010;620:410.
[21] Nikitenko Yu.V. Physics of Particles and Nuclei, v.40, № 6 (2009) 890-947.
[22] V.L. Aksenov, Yu.V. Nikitenko, S.V. Kozhevnikov, Physica B 2001; 297: 94-100.