DOI 10.20310/2686-9667-2019-24-128-368-375
УДК 517.98

Decomposition of boundary representations on the Lobachevsky plane associated with linear bundles

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Разложение граничных представлений на плоскости Лобачевского в сечениях линейных расслоений

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Abstract. Earlier we described canonical (labelled by $\lambda \in \mathbb{C}$) and accompanying boundary representations of the group $G = \mathrm{SU}(1,1)$ on the Lobachevsky plane D in sections of linear bundles and decomposed canonical representations into irreducible ones. Now we decompose representations acting on distributions concentrated at the boundary of D. In the generic case $2\lambda \notin \mathbb{N}$ they are diagonalizable, in the exceptional case Jordan blocks appear.

Keywords: Lobachevsky plane; canonical representations; distributions; boundary representations; Poisson transforms

For citation: Grosheva L.I. Razlozhenie granichnyh predstavlenij na ploskosti Lobachevskogo v secheniyah linejnyh rassloenij [Decomposition of boundary representations on the Lobachevsky plane associated with linear bundles]. *Vestnik rossiyskikh universitetov. Matematika – Russian Universities Reports. Mathematics*, 2019, vol. 24, no. 128, pp. 368–375. DOI 10.20310/2686-9667-2019-24-128-368-375.

Аннотация. Ранее мы описали канонические и граничные представления группы $G = \mathrm{SU}(1,1)$ на плоскости Лобачевского в сечениях линейных расслоений (они нумеруются комплексными числами λ) и разложили канонические представления на неприводимые. Сейчас мы разлагаем представления, действующие в обобщенных функциях, сосредоточенных на границе. В общем случае $2\lambda \notin \mathbb{N}$ они диагонализуемы, в исключительном случае появляются жордановы клетки.

Ключевые слова: плоскость Лобачевского; канонические представления; обобщенные функции; граничные представления; преобразования Пуассона

Для цитирования: *Грошева Л.И.* Разложение граничных представлений на плоскости Лобачевского в сечениях линейных расслоений // Вестник российских университетов. Математика. 2019. Т. 24. № 128. С. 368–375. DOI 10.20310/2686-9667-2019-24-128-368-375. (In Engl., Abstr. in Russian)

In our work [3] we described canonical and boundary representations of the group $G = \mathrm{SU}(1,1)$ on the Lobachevsky plane D in sections of linear bundles on D. Then in [4] we decomposed *canonical* representations into irreducible ones. Now we continue [4] and decompose *boundary* representations. We lean on works [1, 2].

1. The Lobachevsky plane

The Lobachevsky plane is the unit disk $D: z\overline{z} < 1$ on the complex plane with the linear-fractional action of G:

$$z \mapsto z \cdot g = \frac{az + \overline{b}}{bz + \overline{a}}, \quad g = \begin{pmatrix} a & b \\ \overline{b} & \overline{a} \end{pmatrix}, \quad a\overline{a} - b\overline{b} = 1.$$

The boundary S of D is the circle $z\overline{z} = 1$, it consists of points $s = \exp i\alpha$, the measure ds on S is $d\alpha$. Let $\overline{D}$ be the closure of D: $\overline{D} = D \cup S$. Let

$$p = 1 - z\overline{z},$$

so that $D = \{p > 0\}$ and $S = \{p = 0\}$. The stabilizer of the point $z = 0$ is the maximal compact subgroup $K = \mathrm{U}(1)$ consisting of diagonal matrices:

$$k = \begin{pmatrix} a & 0 \\ 0 & \overline{a} \end{pmatrix}, \quad a\overline{a} = 1,$$

so that $D = G/K$. The Euclidean measure $dxdy$ on D is $(1/2)\, dp\, ds$, a G-invariant measure $d\mu(z)$ on D is

$$d\mu(z) = p^{-2} dxdy.$$

If M is a manifold, then $\mathcal{D}(M)$ denotes the space of compactly supported infinitely differentiable $\mathbb{C}$-valued functions on M, with a usual topology, and $\mathcal{D}'(M)$ denotes the space of distributions on M – of antilinear continuous functionals on $\mathcal{D}(M)$.

We use the notation

$$\mathbb{N} = \{0, 1, 2, \ldots\}.$$

Recall principal non-unitary series representations of G trivial on the center, see also [4]. Let $\sigma \in \mathbb{C}$. The representation T_σ acts on the space $\mathcal{D}(S)$ by

$$(T_\sigma(g)\varphi)(s) = \varphi(s \cdot g)|bs + \overline{a}|^{2\sigma}.$$

The inner product from $L^2(S, ds)$:

$$\langle \psi, \varphi \rangle_S = \int_S \psi(s)\, \overline{\varphi(s)}\, ds$$

is invariant with respect to the pair $(T_\sigma, T_{-\overline{\sigma}-1})$.

If $\sigma \notin \mathbb{Z}$, then T_σ is irreducible and equivalent to $T_{-\sigma-1}$ (for $\sigma \in \mathbb{Z}$ there is a "partial equivalence"). For $\sigma = v \in \mathbb{N}$ the representation T_v has an invariant irreducible subspace E_v spanned by $\exp ir\alpha$, $r = -v, -v+1, \ldots, v$.

A basis of the Lie algebra $\mathfrak{g}$ of G is

$$L_0 = \begin{pmatrix} i/2 & 0 \\ 0 & -i/2 \end{pmatrix}, \quad L_1 = \begin{pmatrix} 0 & -i/2 \\ i/2 & 0 \end{pmatrix}, \quad L_2 = \begin{pmatrix} 0 & 1/2 \\ 1/2 & 0 \end{pmatrix}.$$

We also use their linear combinations (they belong to the complexification of $\mathfrak{g}$):

$$L_+ = L_2 + iL_1 = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad L_- = L_2 - iL_1 = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}.$$

Denote by $\Delta_{\mathfrak{g}}$ the twice Casimir element of the universal enveloping algebra $\mathrm{Env}(\mathfrak{g})$ of $\mathfrak{g}$:

$$\Delta_{\mathfrak{g}} = -L_0^2 + L_1^2 + L_2^2.$$

The representation T_σ of $\mathfrak{g}$ assigns to L_0, L_+, L_- the following operators:

$$\begin{aligned} T_\sigma(L_0) &= \frac{d}{d\alpha}, \\ T_\sigma(L_+) &= e^{i\alpha}\left(\sigma + i\frac{d}{d\alpha}\right), \\ T_\sigma(L_-) &= e^{-i\alpha}\left(\sigma - i\frac{d}{d\alpha}\right), \\ T_\sigma(\Delta_{\mathfrak{g}}) &= \sigma(\sigma+1). \end{aligned}$$

2. Canonical representations

Let $\mathcal{D}(\overline{D})$ be the space of restrictions to $\overline{D}$ of functions from $\mathcal{D}(\mathbb{C})$ with the induced topology, and by $\mathcal{D}'(\overline{D})$ the space of distributions on $\mathbb{C}$ with supports in $\overline{D}$. Consider the inner product with respect to the Lebesgue measure on D:

$$\langle F, f\rangle_D = \int_D F(z)\overline{f(z)}dxdy, \quad z = x + iy. \tag{2.1}$$

The space $\mathcal{D}(\overline{D})$ can be embedded into $\mathcal{D}'(\overline{D})$ by assigning to $h \in \mathcal{D}(\overline{D})$ the functional $f \mapsto \langle h, f\rangle_D$, $f \in \mathcal{D}(\overline{D})$.

We shall use denotation:

$$z^{\mu,\, m} = |z|^\mu \left(\frac{z}{|z|}\right)^m, \quad \mu \in \mathbb{C}, \quad m \in \mathbb{Z}.$$

Let $\lambda \in \mathbb{C}$. We define the *canonical representation* $R_{\lambda,m}$ of the group G associated with a character of K as follows:

$$\left(R_{\lambda,m}(g)f\right)(z) = f(z \cdot g)\,(bz + \overline{a})^{-2\lambda-4,2m},$$

it acts on the space $\mathcal{D}(\overline{D})$.

The inner product (2.1) is invariant with respect to the pair $(R_{\lambda,m},\, R_{-\overline{\lambda}-2,m})$:

$$\langle R_{\lambda,m}(g)f,\, h\,\rangle_D = \langle f,\, R_{-\overline{\lambda}-2,m}(g^{-1})h\,\rangle_D, \quad g \in G. \tag{2.2}$$

The formula (2.2) allows to extend the representation $R_{\lambda,m}$ to the space $\mathcal{D}'(\overline{D})$ of distributions on $\overline{D}$.

Here are formulae for basic elements of $\mathfrak{g}$ in variables p and α:

$$R_{\lambda,m}(L_0) = \frac{\partial}{\partial\alpha} - im,$$

$$R_{\lambda,m}(L_\pm) = \mathrm{e}^{\pm i\alpha}\left\{-rp\frac{\partial}{\partial p} \pm \frac{1}{2}(r+r^{-1})i\frac{\partial}{\partial\alpha} - (\lambda+2\mp m)r\right\}. \tag{2.3}$$

Let us also write the operator corresponding to $\Delta_{\mathfrak{g}}$:

$$\begin{aligned} R_{\lambda,m}(\Delta_{\mathfrak{g}}) = (p^3-p^2)\frac{\partial^2}{\partial p^2} + \left[(2\lambda+4)p - (2\lambda+5)p^2\right]\frac{\partial}{\partial p} + \\ + imp\,\frac{\partial}{\partial\alpha} + \frac{1}{4}\cdot\frac{p^2}{1-p}\,\frac{\partial^2}{\partial\alpha^2} + \\ + \left[(\lambda+2)(\lambda+1) - \left((\lambda+2)^2 - m^2\right)p\right]. \end{aligned} \tag{2.4}$$

In (2.4) one has to use the binomial expansions ($r = (1-p)^{1/2}$):

$$r = \sum_{n=0}^{\infty}\binom{1/2}{n}(-1)^n\,p^n, \tag{2.5}$$

$$r^{-1} = \sum_{n=0}^{\infty}\binom{-1/2}{n}(-1)^n\,p^n, \tag{2.6}$$

$$\frac{1}{2}(r+r^{-1}) = \sum_{n=0}^{\infty}\binom{1/2}{n}(1-n)(-1)^n\,p^n. \tag{2.7}$$

Applying these formulae to distributions ζ, we have to keep in mind the following:

$$p^n\delta^{(k)}(p) = (-1)^n\frac{k!}{(k-n)!}\delta^{(k-n)}(p).$$

3. Boundary representations

Canonical representations $R_{\lambda,m}$ generate two boundary representations $L_{\lambda,m}$ and $M_{\lambda,m}$. For simplicity, in this paper we restrict ourselves to the first one. It acts on distributions in $\mathcal{D}'(\overline{D})$ concentrated at S.

Consider distributions of the following form:

$$\zeta = \varphi(s)\,\delta^{(k)}(p),$$

where $\varphi \in \mathcal{D}(S)$ and $\delta(p)$ is the Dirac delta function on the real line (being a continuous linear functional on $\mathcal{D}(\mathbb{R})$) and $\delta^{(k)}(p)$ its k-th derivative. The space of these distributions will be denoted by $\Delta_k(\overline{D})$. Define also

$$\Sigma_k(\overline{D}) = \Delta_0(\overline{D}) + \Delta_1(\overline{D}) + \cdots + \Delta_k(\overline{D}),$$

so that a distribution ζ in $\Sigma_k(\overline{D})$ is a linear combination

$$\zeta = \varphi_0(s)\,\delta(p) + \varphi_1(s)\,\delta'(p) + \cdots + \varphi_k(s)\,\delta^{(k)}(p).$$

We get a filtration:

$$\Delta_0(\overline{D}) = \Sigma_0(\overline{D}) \subset \Sigma_1(\overline{D}) \subset \Sigma_2(\overline{D}) \subset \ldots$$

Let $\Sigma(\overline{D})$ denote the union of all $\Sigma_k(\overline{D})$.

The canonical representation $R_{\lambda,m}$ acting on $\mathcal{D}'(\overline{D})$, preserves the space $\Sigma(\overline{D})$ and the filtration (2.3). The boundary representation $L_{\lambda,m}$ is the restriction of $R_{\lambda,m}$ to $\Sigma(\overline{D})$.

4. Poisson transform

Let λ, $\sigma \in \mathbb{C}$ and $m \in \mathbb{Z}$. We define the *Poisson transform associated with the canonical representation* $R_{\lambda,m}$ as the map $P_{\lambda,\sigma}^{(m)} : \mathcal{D}(S) \to C^\infty(D)$ by the following formula

$$\left(P_{\lambda,\sigma}^{(m)}\,\varphi\right)(z) = p^{-\lambda-\sigma-2} \int_S (1 - s\overline{z})^{2\sigma,-2m}\, s^m\, \varphi(s)\, ds.$$

The Poisson transform $P_{\lambda,\sigma}^{(m)}$ intertwines the representations $T_{-\sigma-1}$ and the canonical representation $R_{\lambda,m}$:

$$R_{\lambda,m}(g)\, P_{\lambda,\sigma}^{(m)} = P_{\lambda,\sigma}^{(m)}\, T_{-\sigma-1}(g) \quad (g \in G).$$

The Poisson transform $P_{\lambda,\sigma}^{(m)}$ is meromorphic in σ, and has poles at the points

$$\sigma = \lambda - k, \quad \sigma = -\lambda - 1 + l \quad (k, l \in \mathbb{N}). \tag{4.1}$$

All poles are simple except in the case when the two sequences (4.1) have a non-empty intersection and the pole belongs to this intersection. This happens when $2\lambda + 1 \in \mathbb{N}$ and $0 \leqslant k, l \leqslant 2\lambda + 1$, $k + l = 2\lambda + 1$. In this case the pole μ is of the second order. Let us write down the principal part of the Laurent series of $P_{\lambda,\sigma}^{(m)}$ at the poles μ of the first order:

$$P_{\lambda,\sigma}^{(m)} = \frac{\widehat{P}_{\lambda,\mu}^{(m)}}{\sigma - \mu} + \cdots.$$

The residue intertwines $T_{-\mu-1}$ with $R_{\lambda,m}$. Let us write it explicitly. We set

$$V_{\sigma,m,n}(p) = (1 - p)^{(m+n)/2}\, F(\sigma + 1 + m, \sigma + 1 + n; 2\sigma + 2; p),$$

where F is the Gauss hypergeometric function. Expand V in powers of p:

$$V_{\sigma,m,n}(p) = \sum_{k=0}^{\infty} w_{\sigma,k}^{(m)}(n)\, p^k,$$

here $w^{(m)}_{\sigma,k}$ are polynomials in n of degree k. The coefficients of these polynomials are rational functions of σ with simple poles. We set

$$W^{(m)}_{\sigma,k} = w^{(m)}_{\sigma,k}\left(\frac{1}{i}\,\frac{d}{d\alpha}\right).$$

If a pole μ belongs only to one of the sequences (4.1), then it is simple. In particular,

$$\widehat{P}^{(m)}_{\lambda,\lambda-k} = (-1)^{k+m}\,\frac{1}{k!}\,a_{-m}(\lambda-k)\,\xi^{(m)}_{\lambda,k}\,,$$

where

$$a_n(\sigma) = 2\pi\,(-1)^n\,\frac{\Gamma(-2\sigma-1)}{\Gamma(-\sigma+n)\,\Gamma(-\sigma-n)}$$

and $\xi^{(m)}_{\lambda,k}$ is the following operator $\mathcal{D}(S)\to\Sigma_k(\overline{D})$:

$$\xi^{(m)}_{\lambda,k}\,\varphi = s^m\,\sum_{n=0}^{k}(-1)^n\,\frac{k!}{(k-n)!}\,\left(W^{(m)}_{\lambda-k,n}\,\varphi\right)(s)\,\delta^{(k-n)}(p).$$

The operator $\xi^{(m)}_{\lambda,k}$ is meromorphic in λ. For fixed $k=1,2\ldots$ it has k poles (simple) at the points $\lambda=k-1,\ k-3/2,\ k-2,\ldots,(k-1)/2$. It intertwines $T_{-\lambda-1+k}$ with $L_{\lambda,m}$ (restricted to $\Sigma_k(\overline{D})$).

Let us write three first operators:

$$\begin{aligned}
\xi^{(m)}_{\lambda,0}\,\varphi &= s^m\varphi\cdot\delta(p),\\
\xi^{(m)}_{\lambda,1}\,\varphi &= s^m\Big\{\varphi\cdot\delta(p)-\frac{1}{2\lambda}(\lambda^2\varphi-m\cdot i\varphi')\cdot\delta'(p)\Big\},\\
\xi^{(m)}_{\lambda,2}\,\varphi &= s^m\Big\{\varphi\cdot\delta(p)-\frac{1}{\lambda-1}\big((\lambda-1)^2\varphi-m\cdot i\varphi'\big)\cdot\delta'(p)\\
&\quad+\frac{1}{4(\lambda-1)(2\lambda-1)}\Big\{\,\big[(\lambda-1)^2\lambda^2+m^2\big]\,\varphi\\
&\quad-2(\lambda-1)(2\lambda-1)\,m\cdot i\varphi'-\big[(\lambda-1)^2+2m^2\big]\,\varphi''\Big\}\cdot\delta''(p)\Big\}.
\end{aligned}$$

5. Decomposition of boundary representations

Theorem 5.1. *The representation $L_{\lambda,m}$ is equivalent to a upper triangular matrix with diagonal $T_{-\lambda-1}$, $T_{-\lambda}$, $T_{-\lambda+1},\ldots$.*

P r o o f. The formulae (2.3) and (2.5)–(2.7) show that operators $R_{\lambda,m}(L^{\pm})$ move subspaces $\Delta_k(\overline{D})$ to $\Sigma_k(\overline{D})$. Also these formulae show that the operator $R_{\lambda,m}(X)$ where $X\in\mathfrak{g}$ moves a distribution $s^m\varphi(s)\,\delta^{(k)}(p)$ in $\Delta_k(\overline{D})$ to the distribution $s^m(T_{-\lambda-1+k}(X)\varphi)(s)\,\delta^{(k)}(p)+\ldots$ in $\Sigma_k(\overline{D})$. □

Let $V^{(m)}_{\lambda,k}$ be the image of $\xi^{(m)}_{\lambda,k}$. This space is contained in $\Sigma_k(\overline{D})$ and its projection to $\Delta_k(\overline{D})$ is the whole $\Delta_k(\overline{D})$. It gives:

Theorem 5.2. *In the generic case* $2\lambda \notin \mathbb{N}$ *the boundary representation* $L_{\lambda,m}$ *is diagonalizable which means that* $\Sigma(\overline{D})$ *decomposes into the direct sum of subspaces* $V_{\lambda,k}^{(m)}$, $k \in \mathbb{N}$, *the restriction of* $L_{\lambda,m}$ *to* $V_{\lambda,k}^{(m)}$ *is equivalent to* $T_{-\lambda-1+k}$ *(by* $\xi_{\lambda,k}$ *), so that* $L_{\lambda,m}$ *is the direct sum of the* $T_{-\lambda-1+k}$ $(k \in \mathbb{N})$.

Now let $\lambda \in (1/2)\mathbb{N}$. This number λ is a pole (of the first order) of $\xi_{\tau,k}^{(m)}$ in τ for $k \in \mathbb{N}$ such that $\lambda + 1 \leqslant k \leqslant 2\lambda + 1$. For example, if $\lambda = 0$, then $k = 1$; if $\lambda = 1/2$, then $k = 2$; if $\lambda = 1$, then $k = 2, 3$; if $\lambda = 3/2$, then $k = 3, 4$. For these λ the spaces $V_{\lambda,k}^{(m)}$ are defined for all $k \in \mathbb{N}$ such that $k < \lambda + 1$ and $2\lambda + 1 < k$, for the others these spaces are absent. Let us write down the Laurent expansion of $\xi_{\tau,k}^{(m)}$ at $\tau = \lambda$:

$$\xi_{\tau,k}^{(m)} = \frac{\widehat{\xi}_{\lambda,k}^{(m)}}{\tau - \lambda} + \mathring{\xi}_{\lambda,k}^{(m)} + \ldots$$

For the indicated k we define the spaces $\widehat{V}_{\lambda,k}^{(m)}$ and $\mathring{V}_{\lambda,k}^{(m)}$ as the images of the operators $\widehat{\xi}_{\lambda,k}^{(m)}$ and $\mathring{\xi}_{\lambda,k}^{(m)}$ respectively. The space $\widehat{V}_{\lambda,k}^{(m)}$ is isomorphic to $V_{\lambda,l}^{(m)}$ where $l + k = 2\lambda + 1$, namely there is a relation $\mathring{\xi}_{\lambda,k}^{(m)}(\varphi) = \xi_{\lambda,l}^{(m)}(\psi)$ where ψ is obtained from φ by means of some operator. Therefore the operator $\widehat{\xi}_{\lambda,k}^{(m)}$ intertwines $T_{-\lambda-1+l}$ with $L_{\lambda,m}$, notice that it vanishes on E_l. The space $\mathring{V}_{\lambda,k}^{(m)}$ has the full projection to $\Delta_k(\overline{D})$.

On the pair $\widehat{V}_{\lambda,k}^{(m)}$, $\mathring{V}_{\lambda,k}^{(m)}$ the representation $L_{\lambda,m}$ is the block

$$\begin{pmatrix} T_{-\lambda-1+l} & * \\ 0 & T_{-\lambda-1+k} \end{pmatrix}.$$

Since $-\lambda-1+l = -(-\lambda-1+k)-1$, representations $T_{-\lambda-1+l}$ and $T_{-\lambda-1+k}$ are isomorphic, so that this block is a genuine Jordan block. Here is the matrix corresponding to the Casimir operator $R_{\lambda,m}(\Delta_{\mathfrak{g}})$:

$$\begin{pmatrix} \mu(\mu+1) & * \\ 0 & \mu(\mu+1) \end{pmatrix},$$

where $\mu = -\lambda - 1 + l$ or $\mu = -\lambda - 1 + k$. Thus, me obtain the following theorem (we use the notation $[a]$ for the integral part of a number a).

Theorem 5.3. *Let* $\lambda \in (1/2)\mathbb{N}$. *Then the space* $\Sigma(\overline{D})$ *is the direct sum of the subspaces* $V_{\lambda,k}^{(m)}$ *with* $k \geqslant 2\lambda + 2$ *and* $k \leqslant \lambda$ *and subspaces* $\mathring{V}_{\lambda,k}^{(m)}$ *with* $\lambda + 1 \leqslant k \leqslant 2\lambda + 1$.

The representation $L_{\lambda,m}$ *is equivalent to the direct sum of* $[\lambda+1]$ *Jordan blocks with the diagonal* $(T_{-\lambda-1+j}, T_{\lambda-j})$, $j = 0, 1, \ldots, [\lambda]$, *acting on subspaces* $V_{\lambda,l}^{(m)} + \mathring{V}_{\lambda,k}^{(m)}$, $k + l = 2\lambda + 1$, *the representation* $T_{1/2}$ *for half-integer* λ, *and the representations* $T_{\lambda+1}, T_{\lambda+2}, \ldots$.

Let us write $\widehat{\xi}_{\lambda,k}^{(m)}$ and $\mathring{\xi}_{\lambda,k}^{(m)}$ for some λ, k.

Let $\lambda = 0$, $k = 1$. Then

$$\widehat{\xi}_{0,1}^{(m)}(\varphi) = \frac{im}{2} s^m \varphi' \delta(p), \quad \mathring{\xi}_{0,1}^{(m)}(\varphi) = s^m \varphi \delta'(p).$$

Let $\lambda = 1$, $k = 2$. Then

$$\widehat{\xi}_{1,2}^{(m)}(\varphi) = ims^m \Big\{ \varphi' \delta'(p) - \frac{1}{2} \left(\varphi' - im\varphi'' \right) \delta(p) \Big\},$$

$$\mathring{\xi}_{1,2}^{(m)}(\varphi) = s^m \Big\{ \varphi \delta''(p) + \frac{1}{4} \left(m^2 - 2im\varphi' + (4m^2 - 1)\varphi'' \right) \delta(p) \Big\}.$$

Let $\lambda = 1/2,\ \ k = 2$. Then

$$\widehat{\xi}^{(m)}_{1/2,2}(\varphi) = \frac{1}{32}(4m^2-1)s^m\left(\varphi + 4\varphi''\right)\delta(p),$$

$$\overset{\circ}{\xi}{}^{(m)}_{1/2,2}(\varphi) = s^m\Big\{\varphi\delta''(p) + \frac{1}{2}\left(\varphi - 4im\varphi'\right)\delta'(p) + \frac{1}{16}\left(4\varphi + im\varphi' + 16m^2\varphi''\right)\delta(p)\Big\}.$$

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Received 13 August 2019
Reviewed 16 October 2019
Accepted for press 29 November 2019

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Поступила в редакцию 13 августа 2019 г.
Поступила после рецензирования 16 октября 2019 г.
Принята к публикации 29 ноября 2019 г.