# PROCEEDINGS

of the Union of Scientists - Ruse

Book 5

## Mathematics, Informatics and Physics

Volume 11, 2014

RUSE

# PROCEEDINGS

**OF THE UNION OF SCIENTISTS - RUSE**




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**of the Union of Scientists – Ruse**



**ISSN 1314-3077**

ISSN 1314-3077

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**BOOK 5**

**"MATHEMATICS, INFORMATICS AND PHYSICS"**

**VOLUME 11**

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**BOOK 5**

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# NUCLEAR CHARGE FORM FACTOR AND CLUSTER STRUCTURE

**Galina Krumova**

*Angel Kanchev University of Ruse*

***To the 70th Anniversary of Prof. Anton N. Antonov***
***with gratitude for the long and beneficial collaboration***

***Abstract:*** *The charge form factor of $^6Li$ nucleus is considered on the basis of its cluster structure. The charge density of $^6Li$ is presented as a superposition of two terms. One of them is a folded density and the second one is a sum of $^4He$ and the deuteron densities. Using the available experimental data for $^4He$ and deuteron charge form factors, a good agreement of the calculations with the experimental data for the charge form factor of $^6Li$ is obtained, including those in the region of large transferred momenta.*
***Keywords:*** *Form factor, cluster structure.*

At the jubilee seminar in honour of Prof. Antonov our dear colleague and co-author Egle Tomasi-Gustaffson briefly outlined the general situation in contemporary theoretical physics:

**Some open questions in Quantum Chromo Dynamics:**

- Why free quarks are not observed?
- Origin of the hadron mass: the Higgs mechanism accounts for some percent of the hadron mass.
- How are colour neutral objects formed?
- Establish existence and properties of exotics, hybrids, glueballs.
- Structure of the nucleon - charge, magnetic, spin distributions.

**Hadron Physics:**

- **From high to intermediate energy – complexity:**

Quark model (Gell-Mann 1964):
- Hadrons are formed by quarks which interact via gluons,
- Baryons are hadrons formed by 3 quarks,
- Mesons are hadrons formed by quark-antiquark.

Hadrons consist of bound systems of ~non-relativistic heavy constituents, coupling is small: non-perturbative effects or higher order corrections can be neglected.

- **From intermediate to low energy – complexity:**

Nuclei: protons and neutrons:
- Light nuclei: the nucleon structure is important,
- Mesons currents,
- Heavy nuclei: statistical effects?

Electromagnetic and strong interactions play a subtle role.

**Hadron Form Factors are the bridge.**

This is the reason for a serious motivation to study nuclear form factors in details.

The problem of the charge form factor of $^6Li$ nucleus is considered successfully in [6]:

Cent. Eur. J. Phys. • 6(3) • 2008 • 491-497
DOI: 10.2478/s11534-008-0091-4

VERSITA

Central European Journal of **Physics**

# Charge form factor and cluster structure of the $^6$Li nucleus

**Research Article**

Galina Z. Krumova[1], Egle Tomasi-Gustafsson[2], Anton N. Antonov[3]*

**CHARGE DENSITY AND FORM FACTOR OF $^6$Li IN RELATION TO THOSE OF $^4$He AND DEUTERON**

We consider the nucleus of $^6$Li as consisting of $\alpha$+d separated clusters, exchanging nucleons.

Theoretical scheme: folding deuteron and $^4$He charge densities [3]. The charge density of $^6$Li is

$$\rho^{ch}_{6_{Li}}(\vec{r}) = \frac{3}{2}\int d\vec{r}'\rho^{ch}_{4_{He}}(\vec{r}-\vec{r}')\,\rho^{ch}_{d}(\vec{r}'). \qquad (1)$$

The charge densities in (1) are normalized to the number of protons Z (Z=3, 2 and 1 for $^6$Li, $^4$He and the deuteron, correspondingly). The definition of the charge form factor is

$$F^{ch}(\vec{q}) = \frac{1}{Z}\int d\vec{r}\; e^{i\vec{q}.\vec{r}}\;\rho^{ch}(\vec{r}). \qquad (2)$$

We consider protons and neutrons; light, exotic nuclei, densities from Hartree-Fock-Bogoliubov (HFB) theory and Large Scale Shell Model (LSSM), Plane-Wave Born Approximation (PWBA) and Distorted- Wave Born Approximation (DWBA).

Our previously obtained results for $^4$He and $^6$Li charge form factors, compared to the available experimental data, are given in **Fig. 1** according to [3]. One can see a good agreement with the data up to q~3 fm$^{-1}$.

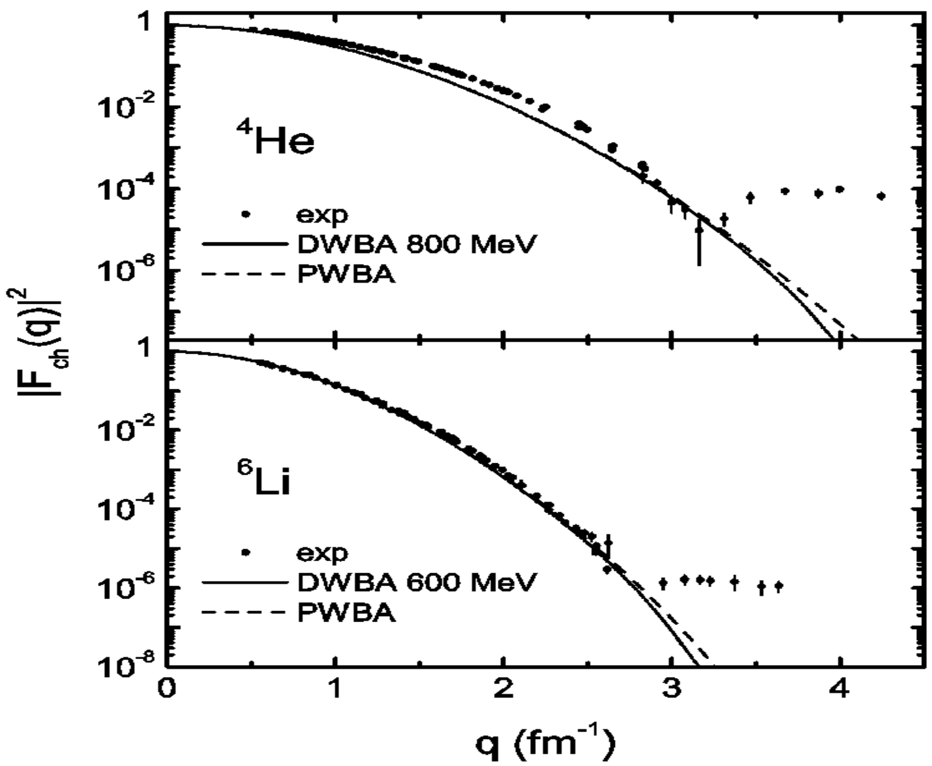


**Fig. 1:** Charge form factors of the stable isotopes $^4$He and $^6$Li obtained in [3], using LSSM densities in PWBA and in DWBA calculations in comparison with the experimental data.

Substituting the charge density (1) in (2) we obtain the following expression for the charge form factor of $^6$Li:

$$F^{ch}_{6_{Li}}(q) = F^{ch}_{4_{He}}(q)\, F^{ch}_{d}(q)\, e^{\frac{q^2}{4A^{2/3}}}, \qquad (3)$$

in which the exponential factor approximately accounts for the centre-of-mass (c.m.) corrections according to [5].

In our calculations of the charge form factor of $^6$Li (3) we use the available experimental data for the charge form factor of $^4$He (see e.g. [4] and references therein), as well as the experimental data for the charge form factor of the deuteron. The latter are those from the Thomas Jefferson Laboratory experiments in which the deuteron charge form factor was measured for a first time to a transferred momentum value up to q=6.64 fm$^{-1}$ and the node of the form factor was observed (Abbott et al. [1, 2]). In our calculations for the deuteron charge form factor we use a best fit parametrization obtained in [7].

In **Fig. 2** are given our results for the squared charge form factor of $^6$Li calculated by (3) (taking account of the c.m. correction) and the experimental data for the charge form factors of $^4$He and the deuteron. For the latter we use the same parametrization with two sets of parameters. A good agreement with the experimental data in the interval of transferred momentum $0<q\leq 2.7$ fm$^{-1}$ can be seen and a disagreement with the values of the form factor for larger q's that are related to small values of r's, i.e. to the central part of the nuclear density. In other words, the central density can be different from the assumption for the folding density (1).

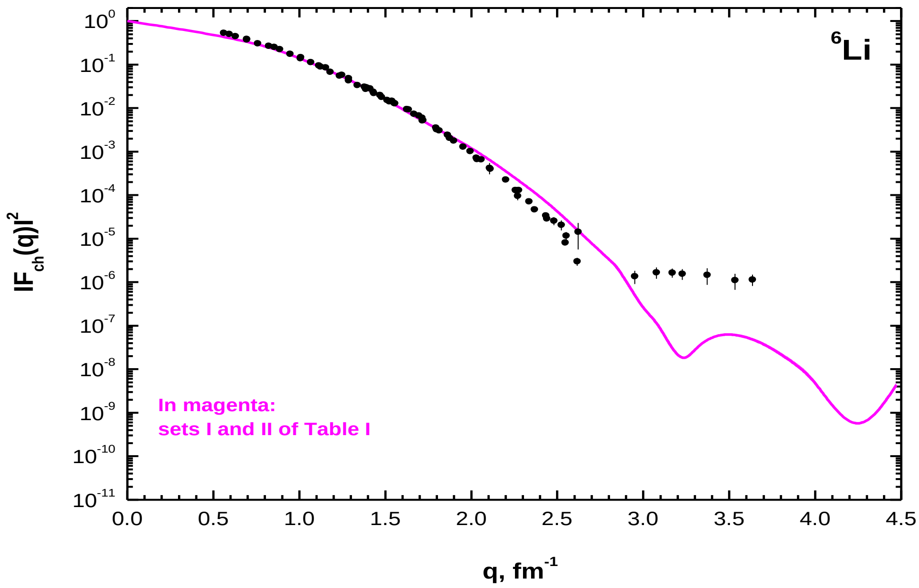


**Fig. 2:** The charge form factor of $^6$Li calculated by using (3) and the experimental data for the charge form factors of $^4$He and the deuteron in comparison with the experimental data.

**DISTINGUISH THE ROLE OF DEUTERON AND $^4$He**

Our second suggestion is to consider the charge density of $^6$Li as a superposition of a folding term and a sum of the charge densities of $^4$He and the deuteron (cluster structure) with weight coefficients $c_1$ and $c_2$, $c_1+c_2=1$ :

$$\rho_{6_{Li}}^{ch}(\vec{r}) = \frac{3}{2} c_1 \int d\vec{r}'\, \rho_{4_{He}}^{ch}(\vec{r}-\vec{r}')\, \rho_{d}^{ch}(\vec{r}')$$

$$+c_2\left[\rho_{4_{He}}^{ch}(\vec{r}) + \rho_{d}^{ch}(\vec{r})\right]. \qquad (4)$$

The form factor is

$$F_{6_{Li}}^{ch}(q) = \left\{c_1 F_{4_{He}}^{ch}(q)\, F_{d}^{ch}(q) + \frac{c_2}{3}\left[2F_{4_{He}}^{ch}(q) + F_{d}^{ch}(q)\right]\right\} e^{\frac{q^2}{4A^{2/3}}}, \qquad (5)$$

$$F_{6_{Li}}^{ch}(0) = 1.$$

Squaring (5) we obtain

$$\left|F_{6_{Li}}^{ch}(q)\right|^2 = A + B + C, \qquad (6)$$

where A, B and C represent the contributions to the charge density of $^6$Li of the folding term (A), of the sum of the charge densities of $^4$He and the deuteron (B) (cluster structure) and the interference term (C). Their explicit expressions are:

$$A = c_1^2 \left|F_{4_{He}}^{ch}(q)\right|^2 \left|F_{d}^{ch}(q)\right|^2 e^{\frac{q^2}{2A^{2/3}}}, \qquad (7)$$

$$B = \frac{c_2^2}{9}\left[4\left|F_{4_{He}}^{ch}(q)\right|^2 + \left|F_{d}^{ch}(q)\right|^2 + 4\left|F_{4_{He}}^{ch}(q)\right|\left|F_{d}^{ch}(q)\right|\right] e^{\frac{q^2}{2A^{2/3}}}, \qquad (8)$$

$$C = \frac{2}{3} c_1 c_2 \left|F^{ch}_{^4He}(q)\right|\left|F^{ch}_{d}(q)\right| \left[2\left|F^{ch}_{^4He}(q)\right| + \left|F^{ch}_{d}(q)\right|\right] e^{\frac{q^2}{2A^{2/3}}}. \quad (9)$$

## RESULTS

**Figs. 3-4** display some of the obtained results.

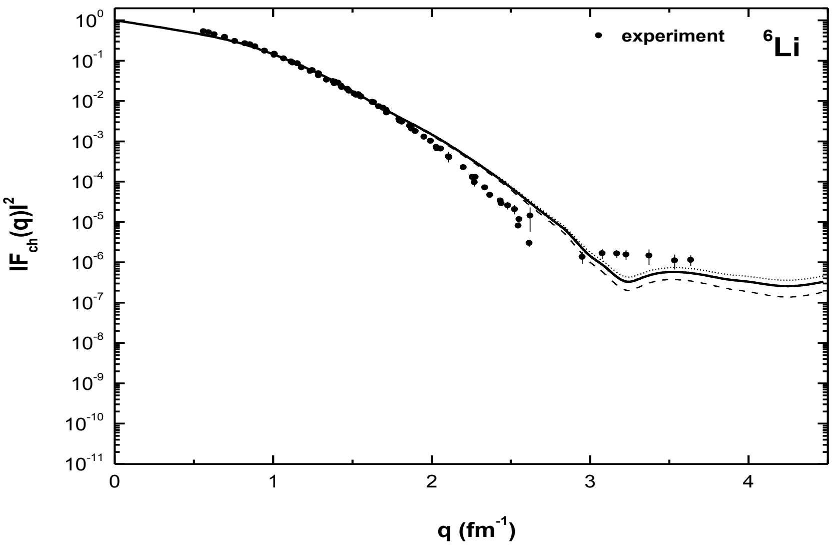


**Fig. 3:** The charge form factor of $^6$Li calculated for $c_1$=0.979, $c_2$=0.021 (solid line); $c_1$=0.975, $c_2$=0.025 (dotted line); $c_1$=0.985, $c_2$=0.015 (dashed line), and in comparison with the experimental data.

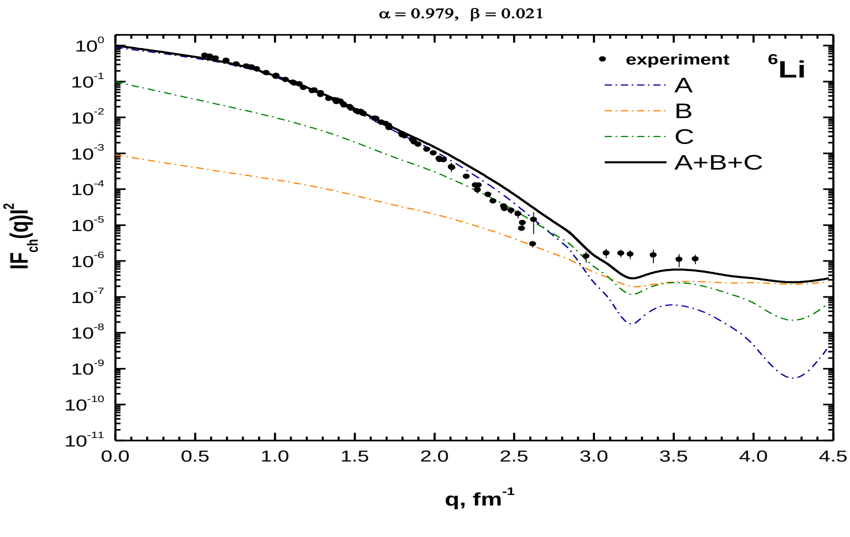


**Fig. 4:** The same as in **Fig. 3**, but for $c_1$=0.979, $c_2$=0.021. The contributions of A, B and C terms are presented.

## CONTRIBUTIONS

Term A dominates up to q=2.7 fm$^{-1}$. B (cluster term) and C (interference term) become important at large q. The shell model α-d cluster structure (sum of $^4$He and d charge densities) is important in the central region and is responsible for the values of the charge form factor at large values of q ≥ 3 fm$^{-1}$.

**CHARGE R.M.S. RADIUS**

Definition:

$$\langle r^2_{^6Li}\rangle = \frac{1}{3}\int d\vec{r}\, r^2 \rho^{ch}_{^6Li}(\vec{r}). \qquad (10)$$

Inserting our density (4) in (10) we obtain

$$\langle r^2_{^6Li}\rangle = c_1\left[\langle r^2_{^4He}\rangle + \langle r^2_d\rangle\right] + \frac{c_2}{3}\left[2\langle r^2_{^4He}\rangle + \langle r^2_d\rangle\right]. \qquad (11)$$

Experimental values for $^4$He and deuteron charge rms radii:

$$\langle r^2_{^4He}\rangle^{\frac{1}{2}} = 1.676(8)fm,$$

$$\langle r^2_d\rangle^{\frac{1}{2}} = 2.116(6)fm.$$

Our result for the charge rms radius of $^6$Li:

$$\langle r^2_{^6Li}\rangle^{\frac{1}{2}} = 2.684\ fm.$$

Experimental value for the charge rms radius of $^6$Li:

$$\langle r^2_{^6Li}\rangle^{\frac{1}{2}} = 2.57(10)\ fm.$$

So the charge rms radius of $^6$Li calculated within the suggested scheme agrees with experimental estimations of this quantity.

**CONCLUSIONS**

- Using a solid theoretical background (VDM, LSSM, PWBA and DWBA),
- superposing two density distributions using the *folding method* and the *existing knowledge* of the distributions,
- with one parameter $c_1$ of clear physical meaning (the weight of the $^4$He contribution) we conclude that:

**The minimum of the charge form factor for $^6$Li (at q=2.9 fm$^{-1}$) is mainly determined by $^4$He structure (for the deuteron this minimum is at q=4.3 fm$^{-1}$, for $^4$He is at q=3.2 fm$^{-1}$).**

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# ЯДРЕНИЯТ ЗАРЯДОВ ФОРМ ФАКТОР И КЛЪСТЕРНАТА СТРУКТУРА

**Галина Крумова**

*Русенски университет „Ангел Кънчев"*

***Посвещава се на 70-ия юбилей на проф. Антон Н. Антонов, с благодарност за дългото и плодотворно сътрудничество***

***Резюме:*** *Зарядовият форм фактор на ядрото на $^{6}$Li се разглежда на базата на клъстерната му структура. Разпределението на зарядовата плътност на $^{6}$Li се представя като суперпозиция от два члена. Единият от тях е сгънатата плътност, а вторият е сума от плътностите на $^{4}$He и деутрона. Използвайки наличните експериментални данни за зарядовите форм фактори на $^{4}$He и деутрона, е постигнато добро съвпадение на пресметнатия и експерименталния зарядови форм фактори на $^{6}$Li, включително в областта на големи предадени импулси.*

***Ключови думи:*** *Форм фактор, клъстерна структура.*

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ISSN 1314-3077