LASER APPLICATIONS

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On the laser method of production of ultracold neutrons

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***Abstract*.** **The laser method of ultracold neutron (UCN) production consists in slowing down thermal neutrons through their repeated elastic collisions with nuclei pre-cooled to a temperature of ~ 1 μK by known methods of laser manipulation of neutral atoms, i.e., this method actually reproduces the known nuclear industry technology in the subthermal range. The feasibility condition for this UCN production process is its short duration, compared with the neutron lifetime. Estimates for a simplified model of the process indicate the possibility of producing the fluxes of UCNs at a concentration several orders of magnitude higher than that obtained with the present method of UCN extraction from the low-energy wing of the Maxwellian energy distribution. Necessary adjustments of the model used for estimates as well as possible applications of the laser method of UCN production are indicated.**

Keywords: *quantum nucleonics, the kinetics of neutron deceleration, laser cooling of neutral atoms, ultracold neutron sources, neutron accelerators, neutron optics, hypothetical extreme cold neutrons.*

1. Introduction

Ultracold neutrons (UCNs) with a temperature $T \sim 10^{-3}$ K and the de Broglie wavelength $\Lambda_{\rm DB} \sim 10^{-5}$ cm are an effective tool of modern experimental physics, successfully using the wave properties of ultracold neutrons in the problems of microscopy, interferometry, etc. [1, 2]. However, wider dissemination of the UCN methods is hindered by the insufficient ($\sim 10^5$ cm^{-2} s^{-1}) flux intensity of UCNs, which are now produced inefficiently by extracting them from the low-energy wing of the Maxwellian energy distribution [1, 2].

A more efficient method of UCN production, noted in [3], is basically similar to the process of production of thermal neutrons by slowing down fast neutrons through their repeated collisions with the nuclei of colder atoms of a coolant. To spread a similar thermodynamic approach to UCNs requires a coolant of an appropriate ultralow temperature. For example, superfluid helium was used as a coolant in the experiment [4]. Other, less exotic and more low-temperature coolants can be the nuclei of atoms cooled to micro-Kelvin temperatures by the known laser methods of manipulation of neutral atoms (see, for example, [5]). The prospects of such laser techniques for the thermodynamic cooling can be illustrated by the following example [3]: a mixture of neutrons with the concentration $n_{\rm n}$ and initial temperature T_0 and of atoms with the concentration $n_{\rm a}$ pre-cooled to a temperature $T_{\rm a}$, would acquire, after the establishment of thermodynamic equilibrium, the overall temperature

$$T = T_0\left(1 + \frac{n_{\rm a}T_{\rm a}}{n_{\rm n}T_0}\right)\left(1 + \frac{n_{\rm a}}{n_{\rm n}}\right)^{-1}. \qquad (1)$$

Thus, for $T_{\rm a} = 10^{-7}$ K and $n_{\rm a} = 10^{13}$ cm^{-3} we can expect the production of UCNs with a temperature $T \sim 3\times 10^{-3}$ K and concentration $n_{\rm n} \sim 10^8$ cm^{-3}, which is four to five orders of magnitude higher than the concentration of UCNs obtained today. The vulnerability of this attractive assessment is evident due to the asymptotic nature of the process of thermodynamic equilibrium establishment: a critical parameter here is the finite time of production of a noticeable number of UCNs, which, of course, should be below both the lifetime (the inverse decay constant) of the β^--active neutron ($\tau_\beta \sim 1300$ s) and the duration of various processes, ceasing its existence.

In this regard, the feasibility of the laser method of UCN preparation requires a study of the kinetics of the cooling process and evaluation of its duration, which is the main motivation for this work. In addition, this paper briefly indicates deviations of model used in the estimates from a real situation and lists various concomitant circumstances (the need for confining the neutrons and coolant in a limited volume, separating a mixture of neutrons and atoms of the coolant after cooling, etc.).

2. Cooling kinetics: estimation of the process duration

The kinetics of neutron energy loss at low energies of collisions with the nucleus should be calculated exactly within the framework of the quantum scattering theory. However, to obtain estimates, it is sufficient, following, for example, [6], to use the model representation of the kinetics of thermodynamic neutron cooling in a spatially homogeneous infinite medium.

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As the neutron energy is much smaller than the energy of possible excitations of internal degrees of freedom of the coolant atoms, the neutron energy loss in a dedicated volume of a homogeneous mixture occurs through elastic collisions. At a large ratio of the de Broglie neutron wavelength to the nucleus size, neutrons with the energy ε in the neutron – nucleus centre-of-mass system scatter isotropically and with equal probability of energy transfer of the nucleus with an average value of $2A\varepsilon(A+1)^{-2}$ to the nucleus in the range from 0 to $4A\varepsilon(A+1)^{-2}$ (A is the mass number of atoms of the coolant). Then, the process of neutron deceleration is characterised by the mean log ratio of the neutron energies before (ε) and after (ε') collisions

$$\ln\frac{\varepsilon}{\varepsilon'} = 1 - \frac{(A-1)^2}{2A}\ln\frac{A+1}{A-1} \equiv \xi(A) \tag{2}$$

and the relative neutron energy loss in each collision

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{\varepsilon - \varepsilon'}{\varepsilon} = 1 - \exp[-\xi(A)], \tag{3}$$

where the averaging is performed over all possible scattering angles [6] (e.g., for ${}^4_2$He, we have $\xi \approx 0.43$, $\Delta\varepsilon/\varepsilon \approx 0.35$, for ${}^{85}_{37}$Rb – $\xi = 0.18$, $\Delta\varepsilon/\varepsilon \approx 0.165$). Most numerical estimates here and below are made for these most experimentally attractive but by no means optimal coolants: helium with an extremely small A whose deep cooling was demonstrated in [7, 8], and rubidium, which is widely used for deep cooling of atoms [5].

It follows from (2) that the energy of the neutrons decreases from ε_0 to ε_N as a result of N successive collisions:

$$N = \xi^{-1}(A)\ln(\varepsilon_0/\varepsilon_N) \tag{4}$$

(e.g., $N = 27$ for helium and 64 for rubidium at $\varepsilon_0/\varepsilon_N = 10^5$).

The time interval between two successive collisions is equal to

$$\Delta t = \left[\sigma(\varepsilon)n_{\mathrm{a}}\left(\frac{2\varepsilon}{M}\right)^{1/2}\right]^{-1} \approx 1.15\times10^{-9}[\sigma(\varepsilon)n_{\mathrm{a}}\varepsilon^{1/2}]^{-1}, \tag{5}$$

where $\sigma = \sigma(\varepsilon)$ is the collision cross section; M is the neutron mass; in the numerical expression, Δt is taken in ns, σ – in cm^2, n_{a} – in cm^{-3}, and ε – in eV.

The cross section $\sigma(\varepsilon)$ generally increases with decreasing energy ε from the reliably measured and tabulated values of σ in the case of thermal ($\varepsilon = 0.0253$ eV) neutrons (e.g., $\sigma = 0.76\times10^{-24}$ cm^2 for helium and 6.4×10^{-24} cm^2 for rubidium [9]). Accurate information about the cross sections for the subthermal neutron energies of interest are scarce, but for some of the atoms (B, In, Au, U, etc.) we can construct analytical expressions accurately describing the empirical dependence of the total cross section, taking also into account elastic collisions, on the energy ε [9]. A typical form of these empirical dependences is

$$\sigma(\varepsilon) \approx q\varepsilon^{-1/2}, \tag{6}$$

where $q = \mathrm{const}$; ε is expressed in eV, q – in cm^2 eV$^{1/2}$. For example, $q \approx 10^{-22}$ cm^2 eV$^{1/2}$ for boron and $q \approx 10^{-23}$ cm^2 eV$^{1/2}$ for gold. Expressions of form (6) clearly reflect the expected general tendency: in the subthermal region the cross section $\sigma(\varepsilon)$ is inversely proportional to the neutron velocity.

For other atoms, the dependences $\sigma(\varepsilon)$ are more complicated than (6), contain the resonances, and, as a rule, increase with decreasing ε. If we assume that this tendency, and the dependence of form (6) are universal enough, the time interval Δt (in ns) between collisions (5) is independent of ε:

$$\Delta t \approx 1.15\times10^{-9}(qn_{\mathrm{a}})^{-1}. \tag{7}$$

Then, the estimate of the total cooling time (in ns) from the neutron energy ε_0 to ε_N is equal to the product of the interval Δt (7) and the number of collisions N (4):

$$\Delta t_N = N\Delta t \approx 1.15\times10^{-9}\ln(T_0/T_N)[\xi(A)qn_{\mathrm{a}}]^{-1}, \tag{8}$$

where T_0 and T_N are the initial and final temperatures of neutrons which are proportional to their energies.

The numerical (but rather arbitrary) example ($\Delta t_N \approx 0.3$ ms for $A = 4$, $q = 10^{-23}$ cm^2 eV$^{1/2}$, $T_0/T_N = 300K/0.003K$ and $n_{\mathrm{a}} = 10^{10}$ cm^{-3}) indicates that the expected value of Δt_N is many orders of magnitude smaller than the neutron lifetime $\tau_\beta \sim 1300$ s and the expected characteristic neutron lifetime (10 – 100 s) impeded by various technological factors.

3. Cooling kinetics: the time law of the neutron temperature fall

Strong inequalities in estimates of the collision number $N \gg 1$ and the relative energy loss $\Delta\varepsilon/(\varepsilon_0 - \varepsilon_N) \ll 1$ allow one to pass from finite differences to differentials ($\Delta\varepsilon/\Delta t \to -\mathrm{d}\varepsilon/\mathrm{d}t$), which leads to a kinetic equation of the cooling process

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = -\varepsilon[1-\exp(-\xi)]\left[\sigma(\varepsilon)n_{\mathrm{a}}\left(\frac{2\varepsilon}{M}\right)^{1/2}\right]$$

$$\approx -\varepsilon Q(\varepsilon, A, \sigma, n_{\mathrm{a}}), \tag{9}$$

where, using (7)

$$Q \approx 0.9\times10^{18}qn_{\mathrm{a}}[1-\exp(-\xi)] \tag{10}$$

(Q is taken in s^{-1}). The solution of kinetic equation (9)

$$\varepsilon(t) = \varepsilon_0\exp(-Qt) \tag{11}$$

reflects a drop in the neutron energy (temperature) in time and is exponential, i.e., an asymptotic approximation to thermodynamic equilibrium.

As noted earlier, the feasibility condition for the laser method of UCN production is the smallness of time required to reduce the temperature of neutrons to the desired one, compared to their lifetime τ_β. Since the most rapid drop in temperature occurs in the initial part of exponent (11), this condition can be reduced to the inequality $Q\tau_\beta > 1$, i.e., in accordance with (10), to

$$Q\tau_\beta \approx 1.1\times10^{21}qn_{\mathrm{a}}[1-\exp(-\xi)] > 1 \tag{12}$$

and then to

$$qn_a > 10^{-21}[1 - \exp(-\xi)]^{-1}, \quad (13)$$

where qn_a is measured in cm^{-1} eV$^{1/2}$. This inequality is usually fulfilled with a wide margin at quite realisable concentrations of the coolant.

From (11) we can obtain the time of neutron cooling from energies ε_0 to ε_Q

$$\Delta t_Q = Q^{-1} \ln(\varepsilon_0/\varepsilon_Q). \quad (14)$$

4. Adjustments of the simple model of the cooling process

Comparison of the two estimates of the cooling time, Δt_N (8) and Δt_Q (14), for the same degree of cooling ($\varepsilon_0/\varepsilon_N = \varepsilon_0/\varepsilon_Q$) indicates their insignificant differences:

$$\frac{\Delta t_N}{\Delta t_Q} = \xi^{-1}[1 - \exp(-\xi)]. \quad (15)$$

Thus, the both practically identical estimates of the cooling duration in a simple model (sections 2 and 3) show that the laser thermodynamic approach to the problem of UCN production is promising. Of course, the experimental situation requires correction of the obtained estimates with account for the rigorous calculation of the deceleration kinetics on the basis of the quantum scattering theory as well as some adjustments for the selected coolants with account for a number of real factors. Let us discuss some of them.

The first thing that needs correction is the form of dependence (6) of the collision cross section $\sigma(\varepsilon)$ of neutrons on their energy ε in the subthermal region. This dependence adopted in the model on the basis of empirical data of some atoms for reasons of physical clearness and computational simplicity, can be significantly more difficult for the coolant chosen due to experimental advantages, though the form of $\sigma(\varepsilon)$ will hardly lose the general trend to increase with decreasing energy ε. Accordingly, finding the duration of the interval Δt (5) between successive collisions may require more complex integration in the energy ε.

To assess the cooling kinetics, use is made of a simple model of a spatially homogeneous infinite medium, whereas in the experiment both the atoms of the coolant and neutrons are in the reactor in the form of spatially joined potential traps of particular types [5]. The design of such a combined reactor can be simplified in the case when it is possible to construct traps with different types of interactions, such as if the atoms of a coolant have an intrinsic electric dipole moment, in contrast to a neutron with a finite magnetic moment. The construction of the potential traps can be optimised by arranging in them a counterflow of neutrons and atoms, which can simplify the extraction of ultracold neutrons produced. Separation of UCNs and the coolant can be also improved by using the abovementioned differences in the types of moments of neutrons and atoms.

Even at fast enough ($\Delta t_N \ll \tau_\beta$) cooling, free protons and electrons are generated due to β^--neutron radioactivity in the reactor volume, which can be removed by applying a weak electric field.

And finally, to produce not only high concentrations of UCNs, but also their large number it is necessary to develop the methods for deep cooling of coolant atoms in the volumes that are considerably higher than those achievable today.

Taking into account the reservation, we present below some estimates that give an idea of the expected orders of magnitudes. The neutron concentration n_n due to the inequality $Q\tau_\beta \gg 1$ is considered constant during the cooling; T_Q is the final temperature of the neutron.

	$^4_2$He	$^{85}_{37}$Rb
T_a/K	10^{-6}	10^{-6}
ξ/A	0.43	0.18
$T_0/T_{N,Q} = \varepsilon_0/\varepsilon_N = \varepsilon_0/\varepsilon_Q$	10^5	10^5
T_0/K	300	300
$T_N = T_Q$/mK	3	3
N	27	64
$\Delta\varepsilon/\varepsilon$	0.35	0.165
$q/10^{-23}$ cm^2 eV$^{1/2}$	0.76	6.4
n_a/cm^{-3}	10^{10}	10^{10}
n_n/cm^{-3}	10^7	10^7
Δt_N/ms	0.4	0.115
Q/s^{-1}	0.24×10^5	10^5
Δt_Q/ms	0.48	0.115
$Q\tau_\beta$	31	130

5. Conclusions

Our analysis indicates the principle possibility of producing (by laser methods) the UCN fluxes at a concentration that is several orders of magnitude greater than the currently available, which gives grounds to plan the initial experiment. For this purpose, it is necessary to make accurate calculations for the selected coolant, as in sections 2 and 3 for a simplified model. In this case, we should take into account both the nuclear (in particular, the desirability of the minimum A and maximum cross section of collisions) and atomic characteristics of the coolant that are the most favourable for deep pre-cooling of atoms, and develop schemes of cooling a large number of atoms.

The successful outcome of the primary experiment would open up new prospects for the traditional areas of physics of ultracold neutrons (neutron optics, interferometry, etc.) [1, 2], as well as for quantum nucleonics, particularly in the problem of UCN loading in new types of accelerators capable of generating directed monoenergetic beams of fast neutrons [3, 10].

Finally, we cannot exclude that the improvement of the discussed method for laser cooling of neutrons would allow the production of extremely cold neutrons with $T \ll 10^{-3}$ K and $\Lambda_{DB} \gg 10^{-5}$ cm. So, it follows from (14) that during the time $\Delta t_Q \approx 0.2$ ms, a suitable coolant can decrease the neutron temperature from $T_0 = 300$ K down to $T_Q = 3$ μK.

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