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# On distant neutron logging (laser methods)

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***Abstract.*** **We discuss the concept of remote inspection of the isotopic composition of objects in space by products of nuclear reactions (including the fission of heavy isotopes), initiated by directed accelerated beams of ultracold neutrons. Despite the partial unavailability of quantitative estimates of specific situations, the proposed approach is internally consistent. We emphasise the urgency of development the problem in question and offer directions for further research.**

***Keywords:*** *quantum nucleonics, ultracold neutrons, laser acceleration of neutrons, inspection of the isotopic composition of remote natural and man-made space objects, fission of heavy nuclei.*

## 1. Introduction

Neutron logging as a method for determining the chemical composition of the substance, invented by Bruno Pontecorvo [1], involves an analysis of the results of interaction of the material of the inspected object with neutrons of a source located near the object, almost in contact with it. For example, in the practice of logging during a geological exploration, the neutron source and recording equipment are placed directly in the depth of a drilled well, and the measurement results are transmitted to the surface via a cable.

The aim of this paper is to draw attention to the prospects for significant expansion of applications of the method through the development of remote contactless neutron logging [2], eliminating the limitations associated with the close proximity of the neutron source and recording equipment. A prerequisite for the discussion of this problem are the physical foundations (discussed in [2–5]) of the laser generation of monokinetic beams of ultracold neutrons (UCNs) with high energies and intensities.

If we assume that the object of remote logging is at a distance of $L \sim 100$ km, the presence of absorption of both probing neutron beams and products of the reaction excited by these beams in the medium attributes the available inspected space to the upper atmosphere and outer space, and the objects of inspection – to astronomical bodies or artificial man-made devices.

Below we discuss the general concept of remote neutron logging and present simple expressions for estimating the expected parameters as well as outline some problems to be solved in the development of this concept.

## 2. Kinematic parameters of beams of UCNs

The process of generation of intense beams of fast UCNs, in accordance with [2–5], takes place in two stages.

1. Production of UCNs with a high concentration by the energy exchange of thermal neutrons with neutral atoms [4] (preliminary deeply cooled with the help of known laser methods [6]), as well as the optimisation of their kinematic parameters in a controlled coaxial magnetic trap [5].

2. Acceleration of produced UCNs with a high concentration during their simultaneous straight-line [2] or pendulum-like [3] motion. In this case, it is assumed to maintain, during acceleration, the initial low temperature and high concentration of neutrons, which requires reliable experimental confirmation.

The expected parameters of UCN fluxes, significant for the considered problem of remote logging, in the order of magnitude are as follows [2–5]: temperature $T \leqslant 10^{-3}$ K (the hypothetical possibility of its subsequent reduction down to a temperature of extremely cold neutrons $T \sim 10^{-6}$ K is also admitted), thermal velocity $u_T \sim 50$ cm s$^{-1}$, concentration $n_\mathrm{n} \sim 10^7$ cm$^{-3}$, transport velocity after acceleration $u_L \sim 10^7 - 10^9$ cm s$^{-1}$, transport kinetic energy $E_\mathrm{kin} \sim 50$ eV – 500 keV, flux density of particles $10^{14} - 10^{16}$ cm$^{-2}$ s$^{-1}$ and energy flux density $10 - 10^3$ W cm$^{-2}$.

These parameters determine the expected kinematics of the neutron flux: the divergence of the neutron beam $\Delta\Omega \sim (u_T/u_L)^2 \sim 10^{-10} - 10^{-14}$ sr (comparable to $\Delta\Omega$ of an optical laser); the delivery time of neutrons $\Delta t_L = L/u_L$ at a distance $L$; the vertical gravitational shift (‘fall’), $\Delta h_\mathrm{g} = (g/2)(L/u_L)^2$, of neutrons at a distance $L$, which is to be taken into account when calculating the trajectories ($g$ is the gravitational acceleration); the weakening of the neutron flux at a distance $L$ at a height $h$ above sea level, characterised by an equivalent thickness $\delta$ of the absorbing layer of water.

Estimates for the fluxes of accelerated UCNs with a high concentration at the transport energy $E_\mathrm{kin}$ [2–5], namely, a short delivery time $\Delta t_L$ and low intensity loss level in the rarefied environment over distances $L$ of hundreds of kilometres, summarised in Table 1, indicate the potential prospects for the use of UCNs in the practice of remote logging, and, in particular, some of their advantages over the beams of photons and charged particles.

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**Table 1.**

| $L$/km | $E$/keV | $\Delta t_L$/ms | $\Delta h_g$/cm | $h$/km | $\delta$/cm |
|---|---|---|---|---|---|
| 10 | 100 | 2.35 | $2.7 \times 10^{-3}$ | – | – |
| 10 | 1000 | 0.75 | $2.8 \times 10^{-4}$ | – | – |
| 100 | 100 | 23.5 | $2.7 \times 10^{-1}$ | – | – |
| 100 | 1000 | 7.5 | $2.8 \times 10^{-2}$ | – | – |
| 10 | – | – | – | 100 | $\sim 10^{-2}$ |
| 100 | – | – | – | 100 | $\sim 10^{-1}$ |
| 10 | – | – | – | 180 | $\sim 10^{-5}$ |
| 100 | – | – | – | 180 | $\sim 10^{-4}$ |

## 3. Inspection of the isotopic composition

As a result of penetration of the flux of accelerated UCNs in the inspected object, there occurs their heating during the partial transfer of the transport kinetic energy to the degrees of freedom of random motion. The isotopic composition of the object is identified by the type and energy spectrum of the characteristic products of nuclear reactions excited by probing neutrons. It is important to specify that the remote implementation of this operation is a complex task, subject to a separate development, in some cases – with a rather problematic possibility of solving it.

Of particular interest is the test of the isotopic composition to fission heavy nuclei. Details of this type of inspection are radically due to different and sometimes inaccessible design features and isotopic composition of the object. Because to get any accurate quantitative data on specific situations is hardly possible, we have to restrict ourselves to the following qualitative considerations.

Of course, to inspect such objects only makes sense before the start of a chain reaction of fission of heavy isotopes in them, i.e., in the subcritical regime without increasing the number of neutrons ($\mathrm{d}N/\mathrm{d}t < 0$) and with a negative exponent ($K - 1 < 0$) in the standard expression (see, for example, [7])

$$N = N_0 \exp\left(\frac{K-1}{\tau} t\right), \tag{1}$$

describing the kinetics of the process of multiplication of the number of neutrons $N(t)$ (without regard to details, such as the delayed secondary neutrons, etc.). Here, $\tau$ is the lifetime of one generation of neutrons (for thermal neutrons it is about 1 ms);

$$K = \nu f P \tag{2}$$

is the neutron breeding factor; $\nu$ is the number of secondary neutrons in one fission event; $f \leqslant 1$ is the fraction that is suitable for further reaction in the next generation; $1 - P$ is the fraction of neutrons leaving the volume $V$ containing the isotopes;

$$N_0 \approx M \frac{\tau}{\tau_{\mathrm{f}}} \nu P \tag{3}$$

is the initial number of neutrons produced by spontaneous fission $M$ of nuclei with time $\tau_{\mathrm{f}}$; $t$ is the time.

Possibility of inspection is inherent in a controlled extraneous injection of neutrons at a rate $I$ from the outside into the volume $V$ containing the isotopes, i.e., a change in the kinetic equation, whose integral is expression (1), by introducing an additional term $I$:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{N}{\tau}(\nu f P - 1) + I. \tag{4}$$

The integral of the modified equation (4)

$$N = N_0 \exp\left(\frac{K-1}{\tau} t\right) - \frac{\tau I}{K-1}\left[1 - \exp\left(\frac{K-1}{\tau} t\right)\right] \tag{5}$$

significantly differs from (1) by the appearance of the second term, proportional to the rate of injection $I$. Now, the kinetics of the number of neutrons $N(t)$ depends not only on the breeding factor $K$, but also on the rate of injection, and, therefore, the increase in the number of neutrons $N$ may begin with $K < 1$, i.e.,

$$\frac{\mathrm{d}N}{\mathrm{d}t} > 0, \text{ if } I > I_{\mathrm{thr}} \equiv -\frac{N_0}{\tau}(K-1) = -\frac{M}{\tau_{\mathrm{f}} f} K(K-1), \tag{6}$$

$I_{\mathrm{thr}}$ not exceeding the maximum value

$$I_{\mathrm{thr}} \leqslant I_{\mathrm{thr}}^{\max} \equiv \frac{M}{4 f \tau_{\mathrm{f}}}, \tag{7}$$

achieved at $K \equiv \nu f P = 1/2$. For example, for $^{235}_{92}\mathrm{U}$ with $\tau_{\mathrm{f}} = 0.98 \times 10^{19}$ years [8] the estimates of the maximum threshold value are as follows: $I_{\mathrm{thr}}^{\max} \approx 0.83 \times 10^{-26}(M/f)$, or in the object volume $V$ with condensed filling by the uranium isotope $I_{\mathrm{thr}}^{\max} \approx 2.5 \times 10^{-4}(V/f)$.

In the light of the above remark about the possibility of only qualitative assumptions about the inspected objects, expression (6), (7) should be regarded as an indication of the way to obtain further estimates of the required values of $I_{\mathrm{thr}}^{\max}$; these estimates can be used for comparison with the expected values of the parameters of the beams of accelerated UCNs [2–5].

The level and composition of the detected radioactive signal of the inspected object depends on the depth of the inequalities (6). In accordance with (6), there can be several scenarios of injection inspection with respect to the degree of deviation of the signal from the background level under the influence of the probing neutrons.

(i) Continuous (quasi-cw) injection with an extremely small excess of the critical level (shallow inequality $I > I_{\mathrm{thr}}$), a slow increase in the number of neutrons $N$ and a weak excess of the recorded signal over the background signal.

(ii) Continuous (quasi-cw) injection with the critical value $I = I_{\mathrm{thr}}$ and the establishment of a stationary process of the fission reaction, which is hardly feasible because of the difficulty of maintaining $I = I_{\mathrm{thr}} = \mathrm{const}$.

(iii) Pulsed injection of duration of a few $\tau$, resulting in a short-term establishment of a supercritical value of $I > I_{\mathrm{thr}}$ and emergence of a chain reaction, immediately decaying after the end of the injection pulse, which is recorded by a significant but short-term increase in the signal (and the same injection with repetitive pulses).

(iv) Longer pulsed supercritical injection with $I > I_{\mathrm{thr}}$, initiating a chain reaction until the destruction of the inspected object, but interrupted before the catastrophic development of the avalanche process.

(v) Continuous injection with deep inequality $I \gg I_{\mathrm{thr}}$ able to cause even a full-scale avalanche chain reaction.

It should be emphasised that in scenarios (iv) and (v), which in fact have already an active impact on the inspected object, the above-mentioned problem of remote analysis of reaction products and identification of the object is greatly simplified.

## 4. Conclusions

The performed discussion is to sketch an approach to solving the urgent problems of inspection of space objects in terms of their potential radioactive threats, identification of ‘space debris’, in the programs of manned and automated space travels, astrophysical research, and attempts to counteract the so-called asteroid hazard, etc. The approach (without exact quantitative results for specific situations), which is internally consistent, also serves as an outline of future research programs, primarily aimed at experimental confirmation of the results of [2–5] that form the basis of the concept of remote neutron logging, at calculation of specific situations and at development of principles of recording and analysing the products of nuclear reactions initiated by the probing neutrons.

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