Possible anomalous interactions of ultracold neutrons

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Under conditions such that the energy of ultracold neutrons is quantized in a gravitational field **g** and the motion of the neutrons is two-dimensional, their elastic cross section is $\propto v^{-1}$. The neutron-emission channel is suppressed in nuclear reactions with ultracold neutrons. An n_2 molecule might form if the motion of the neutrons were one-dimensional.

1. Examining the problem of the storage of ultracold neutrons on a plane (a substrate) in a gravitational field **g**, Lushchikov and Frank[1] actually proposed a method for producing two-dimensional neutrons (2D n's) in free 2D motion along a substrate. The energies of the first gravitational levels are $E_1 = 1.4$ and $E_2 = 2.45$ (in units of 10^{-12} eV). For such ultracold neutrons, one might expect the earth's gravitational field to affect the nature of nuclear interactions. We will be discussing the particular case of a **g** field here, but everything we say applied to any field which presses neutrons against a surface, e.g., magnetic fields and centrifugal-force fields. We restrict the discussion to the elastic scattering of 2D n's (with spins $\uparrow\downarrow$) in the first gravitational level, with a relative-motion energy $\epsilon < E_2 - E_1$ (transitions to other gravitational levels cannot occur).

2. Polarized 2D n's are moving along a substrate which is at $z \leqslant 0$ in the xy plane (Fig. 1). To describe the scattering of the neutrons, we use a Fermi pseudopotential $V_F(|\mathbf{r}_1 - \mathbf{r}_2|) = 4\pi\alpha\hbar^2 m^{-1}\delta(\mathbf{r}_1 - \mathbf{r}_2)$, where m is the mass of a neutron, $\alpha \simeq -17.6$ fm is the scattering length, and $\mathbf{r}_1$ and $\mathbf{r}_2$ are 3D radius vectors. We focus on the 2D motion of the interacting particles as a whole, and we consider their relative 2D motion along the substrate. The wave functions before (i) and after (f) the scattering are $\psi_{i(f)} = \varphi(z_1)\varphi(z_2)(2\pi\hbar)^{-1}\exp[i\mathbf{K}_{i(f)}\vec{\rho}/\hbar]$, where the functions φ are the localized wave functions of the first gravitational level, and $\mathbf{K}_i$,$\mathbf{K}_f$, and $\vec{\rho}$ are the momenta and radius vector of the relative motion of the 2D n's. The scattering probability is $dw_{fi} = 2\pi\hbar^{-1}|U_{fi}|^2\delta(E_f - E_i)d\mathbf{K}_f$, where $U_{fi} = \int\psi_f^* \times V_F\psi_i d\rho dz_1 dz_2$. In specific calculations we use the variational wave function $\varphi(z) = 2\beta^{3/2} z\exp(-\beta z)$, $z \geqslant 0$, where $\beta = (3m^2 g/2\hbar^2)^{1/3} \simeq 1.55\times 10^5$ m^{-1}, $g = 9.8$ m/s^2, and $E_1 \simeq 1.966(\hbar^2 g^2 m)^{1/3} \simeq 1.49\times 10^{-12}$ eV. We then have $U_{fi} = 3\alpha\beta/8\pi m$. To find the scattering cross section $d\sigma$, we divide the probability dw_{fi} by the flux density of the colliding particles, J. Here $d\sigma$ has the dimensionality of a length, in contrast with that in 3D motion (in weightlessness), which is the dimensionality of an area.

Some simple considerations explain this point. In 2D motion, the distribution of the neutrons along the z axis is determined completely by the localized wave functions $\varphi(z_1)$ and $\varphi(z_2)$. In a flux of 2D n's, there can be no more than one particle with a particular set of quantum numbers in a gravitational level. The number of 2D n's which cross a segment of unit length (in the xy plane) oriented perpendicular to the

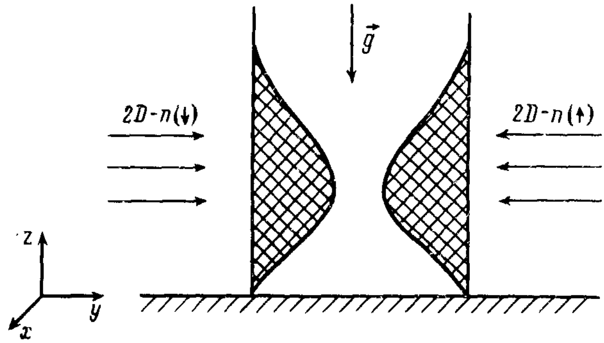

FIG. 1.

direction in which the particles are moving therefore determines the flux density of 2D n's, i.e., $J = v(2\pi\hbar)^{-2}\int dz_1 dz_2 \varphi^2(z_1)\varphi^2(z_2) = v/(2\pi\hbar)^2$, where $v = K_i/\mu$ is the velocity of the relative motion of the 2D n's, and $\mu = m/2$. Taking the identical nature of the particles into account, we find the following expression for $d\sigma$:

$$d\sigma = (9/8)\pi\hbar\alpha^2\beta^2 m^{-1/2}\epsilon^{-1/2}d\theta, \qquad (1)$$

Here an integration has been carried out over the final momenta K_f: $d\mathbf{K}_f = K_f dK_f d\theta$; where $d\theta$ is the angle from the direction of $\mathbf{K}_f$ in the xy plane, $\int d\theta = 2\pi$, and $\epsilon = \mu v^2/2$. In general, the presence of the substrate and the pressing field requires the solution of Faddeev equations in order to describe the scattering of 2D n's. It has been found that solving these equations leads within $|\alpha|\beta \sim 10^{-9}$ to the expression in (1) for any model of the $(\uparrow\downarrow)$ neutron interaction potential. For the total scattering cross section we find $\sigma = (9/4)\pi^2\hbar\alpha^2\beta^2 m^{-1/2}\epsilon^{-1/2}$ from (1). It is important to note that for energies of the ultracold neutrons at which the quantization in the pressing field becomes important the elastic cross section σ has an energy dependence $\propto \epsilon^{-1/2}$, while in weightlessness (3D neutrons) we have $\sigma^{(3D)} = \text{const}$ as $\varepsilon \to 0$. To compare the relative interaction efficiencies of 2D and 3D n's, we compare the number of scattered 3D n's in a unit flux of ultracold neutrons across an area of $L \times L$ and the number of 2D n's in a unit flux across a "transverse dimension" of size L (in the xy plane), where $L = \int z\varphi^2(z)dz = 3/2\beta \simeq 9.7 \times 10^{-6}$ m. In this sense we can say that the cross section for the scattering of the 2D n's is "three-dimensional:" $\sigma^{(2D)} = \sigma L$. With $\epsilon = 10^{-12}$ eV we thus have $\sigma^{(3D)}/\sigma^{(2D)} \simeq 1.5$. Figure 2 shows the low-energy behavior of the cross section for elastic scattering of neutrons (in a gravitational field). The dashed part of the line schematically shows the energy interval in which the ultracold neutrons can undergo transitions between different gravitational levels. A detailed analysis of this region is an independent problem.

3. By forming grooves on the substrate, one can obtain one-dimensional neutrons (1D n's) in a **g** field. These neutrons move freely along a groove. For a wedge-profile groove with a wedge angle $\sim 1°$, the lower energy level is $\sim 10^{-10}$ eV, and the localization height of the wave function is $\sim 10^{-4}$ m. We will use the example of 1D n's to discuss at a qualitative level the possibility of a change in the course of a nuclear

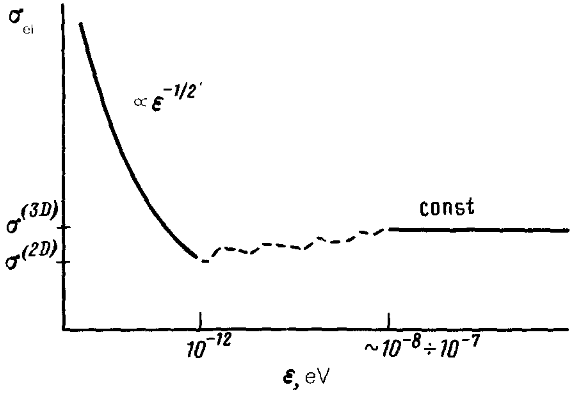

FIG. 2.

reaction. Let us assume that a 1D n with an energy $\sim 10^{-10}$ eV is moving along a groove. At a height $\sim 10^{-4}$ m (from the bottom of the groove) there is an atom with an energy $\sim 10^{-8}$ eV (free atoms can be cooled to $\simeq 3\times 10^{-7}$ K; Ref. 2). In nuclear reactions with slow neutrons, a compound excited nucleus typically forms after the absorption of a neutron. A compound nucleus can decay by a variety of mechanisms, one being neutron emission. In our case, the compound nucleus can emit a neutron only along the groove, since all other directions are forbidden (the g field and the surface of the material serve as an "ideal resonator"). As a result, the decay mechanism compound nucleus→nucleus + n is completely or partially suppressed. This situation corresponds to an increase in the probability for the nuclear reaction (a sort of gravitational catalysis).

Note also that for 1D n's obtained by size quantization in a channel (inside a material) of diameter $\sim\lambda$, where λ is the limiting wavelength ofthe ultracold neutrons, an n_2 bound state can form. In this state the size of the molecule along the channel is $\sim$1–10 m (according to a calculation by a variational method).

4. If ultracold neutrons were put in a centrifuge, the value of g could be increased significantly, making the effects described above observable at neutron energies $\sim 10^{-10}$–10^{-8} eV (this possibility was pointed out by M. V. Kazarnovskiĭ). Such energies are already attainable experimentally.

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[1]V. I. Lushchikov and A. I. Frank, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 607 (1978) [JETP Lett. **28**, 559 (1978)].
[2]P. E. Toschek, Usp. Fiz. Nauk **158**, 451 (1989).

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