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Experimental Search for Molecular-Nuclear Transitions in Water[*]

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Experimental search for molecular-nuclear transitions $H_2O \rightarrow$ $^{18}Ne^* (4.522, 1^-) \rightarrow {}^{18}F \rightarrow {}^{18}O$ in water molecules was carried out. The measurements were performed in a low-background laboratory at the Baksan Neutrino Observatory. Under the assumption that the above transitions take place, the estimate for the half-life time of water molecule was found to be about 10^{18} years.

I. INTRODUCTION

Phenomenon of a long-range effective interaction in some quantum systems including constituents which are only interacting at short distances is known already for a long time. Here, by a short-range interaction we understand any interaction that falls off at large distances between particles, i. e. as $r \longrightarrow \infty$, not slower than exponentially. In the context below, longe-range forces decrease at infinity as some inverse powers of r.

The most pronounced manifestation of this phenomenon appears in the so-called "Efimov effect" [1]. The Efimov effect consists, in particular, in arising an effective interaction between a particle and a coupled pair of particles which behaves as $1/r^2$. A sufficient condition for this effect to take place in a three-bosonic system is a closeness of the binding energies at least for two of pair subsystems to zero. Just the very small binding energies force the two-body wave function to be extremely extended generating an effective long-range interaction of the coupled pair with a complementary particle.

Another example of a long-range effect of short-range interaction was found by Ya. B. Zeldovich [2]. He showed that if two particles interact via two potentials, a short-range one and an arbitrary long-range (say, Coulomb) one, then the spectrum of the two-body system can be drastically changed as compared to the case of a long-range potential only. This change takes place if the short-range potential generates a bound or resonant state with an energy sufficiently close to zero.

Thus, in both the above cases, long-range effects take place due to the fact that a short-range interaction causes a two-body system to be, nevertheless, very extended. Having this in mind, one can expect some enhancement for the probability of transition of the system
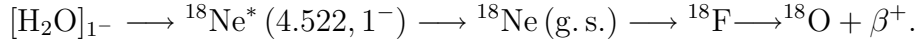

TABLE I. Two examples of nuclear systems with near-threshold resonances

Few-Atomic System			Composed Nuclear System (CNS)			
Molecular System	Nuclear Subsystem (NS)	Energy of NS over g.s. of CNS (MeV)	Nucleus	J^π	E(MeV)	Γ(keV)
H_2O	$^{16}O + p + p$	4.522	^{18}Ne	1^-	4.519	< 9
OH^-	$^{17}O + p$	5.607	^{18}F	1^-	5.604	< 1.2

from a molecular state to an extended (resonance) nuclear state as compared to a similar transition into a localized nuclear state. Indeed, model calculations [3] of the overlap integral between wave functions of the H_2O (1^-) molecule and a resonant state $(4.522, 1^-)$ of the nucleus ^{18}Ne show an enhancement of this sort.

The purpose of the present experiment is to estimate the life time of water molecules with respect to the following decay chain

$$[H_2O]_{1^-} \longrightarrow {}^{18}Ne^* (4.522, 1^-) \longrightarrow {}^{18}Ne\,(g.\,s.) \longrightarrow {}^{18}F \longrightarrow {}^{18}O + \beta^+.$$

II. EXPERIMENTAL APPROACH AND RESULTS

A number of examples of nuclear systems with near-threshold resonances were analyzed from this point of view, among them are $(p, p, {}^{16}O)$ and $(p, {}^{17}O)$ [4,5], i.e. the nuclear constituents of the usual water molecule H_2O and hydroxyl ions OH based on the rare oxygen isotope ^{17}O (see Table I).

For the fist experimental study in this direction we choose the system $(p, p, {}^{16}O)$, i.e. the H_2O molecule. Its properties, in addition to obvious availability, make this case the most favorable for the experiment. From Fig. 1, displaying the energy-lever diagram for ^{18}Ne-nucleus, it is seen that rotation states 1^- of a water molecule and a highly excited state $(1^-, 4.522$ MeV$)$ of this nucleus can be considered as energy degenerate. Thus, a real physical state with these quantum numbers appears to be a superposition of molecular and nuclear states. Experimental approach was designed with taking into account of the properties of both the components of the superposition pair.
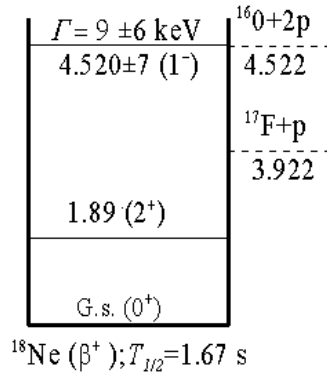

FIG. 1. Fragment of the nucleus ^{18}Ne spectrum.

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As a rule, rotational states are excited only in free molecules while their population under the conditions of condensed-phase water is prohibited due to powerful hydrogen bonds [6]. This makes carrying out the experiments more difficult, but at the same time it gives additional opportunities to manipulate with the hypothetical process of molecular-nuclear transitions in a water system. So, it becomes possible to use an accumulation-measuring cycling during searching for resulting radioactive products. The layout of measurements is shown in Fig. 2. The accumulation cycle represented heating the water portion within a sealed out measuring chamber to a critical point about 647 K, at which a total amount of water was for sure in a vapor phase regardless of pressure within the volume. To withstand this rather a high pressure (22.5 MPa [7]), the stainless-steel or titanium chambers were strengthened for the heating period by two thick steel removable plates at the top and bottom of the chambers. The latter were thick-wall shortened metallic cylinders, sealed at the faces by thin membranes almost fully transparent for the expected annihilation radiation $E_\gamma = 511$ keV.

For the measuring period, the plates were removed, and the chamber was placed after cooling between two NaI(Tl)-scintillators, operating in the $\gamma\gamma$-coincidence mode. First, the measurements were performed in surface-laboratory conditions at the Institute of Physics and Technology Problems (Dubna), then the main part of the experiments was undertaken, this time at a deep underground laboratory of the Baksan Neutrino Observatory (Republic of Kabardino-Balkaria, the North Caucasus) of the Institute for Nuclear Research of the Russian Academy of Sciences. At the surface-laboratory stage, necessary measurement procedures were optimized, and a yield of molecular-nuclear transition in water in the condensed state was estimated. Analysis of these data showed main sources of the background counting: true coincidences due to the cosmic muons, decay of the natural ^{40}K and daughter products of ^{222}Rn (^{214}Bi and ^{214}Po). To take into account the background in the region of "interest", i. e., near $E_\gamma = 511$ keV, some control background measurements were carried out under the identical conditions (geometry, amount of water, *etc.*), in which heavy water (D_2O, 99.0%-enrichment) was used instead of the natural one. Within the limits of statistical fluctuations, both the spectra were identical. For the water half-life in the condensed-phase state with respect to decay by the chain $H_2O \longrightarrow ^{18}Ne(\beta^+; 1.7\,s) \longrightarrow ^{18}F(\beta^+; 109\,min)$, a lower limit was estimated as $T_{1/2} \geq 4.10^{21}$ years (within the 99%-confidence level). At the Baksan Observatory, all the efforts were made to subdue the background radiation as much as possible. The cosmic muons were subdued due to power shielding, as the measuring premises were situated inside a gallery created within the mountain Andyrchi (one of mountains of the Elbrus environment, where the screening thickness of a rock achieves about 600 m of water equivalent. Walls (the ceiling and floor, as well) were built of a special uranium-free concrete. The scintillators were prepared on the basis of materials with a low containment of potassium and radium. They were, for a long time, located in a deep underground. Thus all short-lived cosmic-ray-induced activities should be extinct. The detection unit was provided with an additional shielding composed of interchanged layers of pure tungsten, lead, and copper.

For every γ-quantum event, the time was registered with a channel width 10 s. This was more than sufficient for a detailed analysis of the time dynamics in the range of interest for this experiment. The accumulation interval was chosen to be about three half-lifes of ^{18}F, i. e. 5.5 hours. The measuring time-schedule for these runs is inserted in Fig. 3. Intervals of about four half-lifes of ^{18}F, i. e. ~ 440 min each, were considered as time-periods when the decay of hypothetically accumulated ^{18}F could yet give some contribution to the counting in the region of $E_\gamma = 511$ keV. The remaining part of measuring cycles was used to calculate
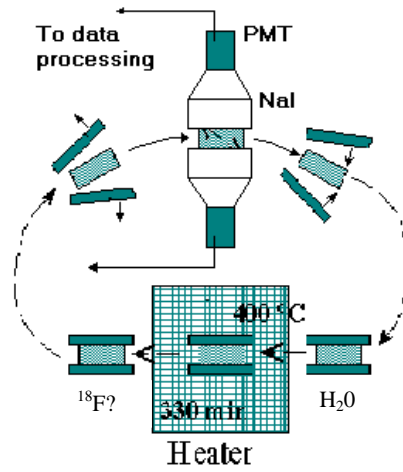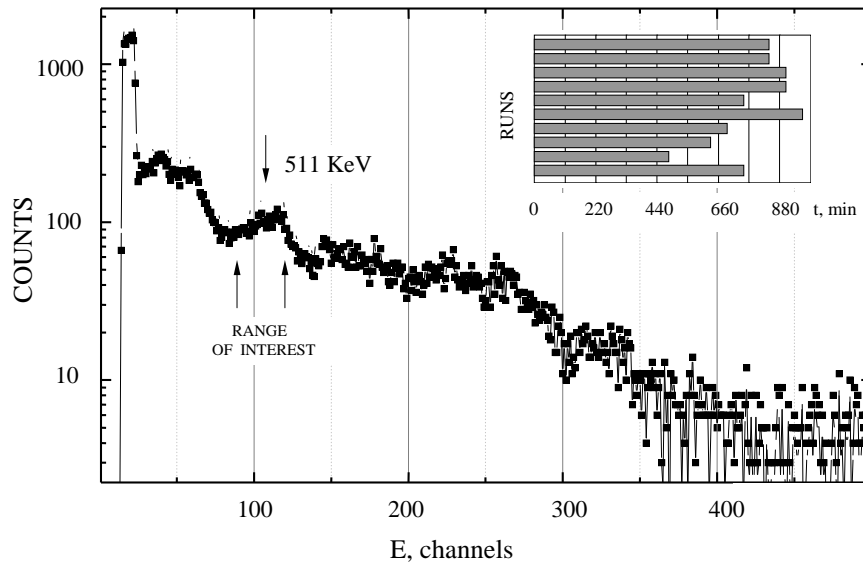
FIG. 2. Scheme of accumulation-measuring procedure.

FIG. 3. The $\gamma\gamma$-coincidence spectrum obtained during ten measuring cycles. Marked by arrows is an energy region around $E_\gamma = 511$ keV. Time-durations of measuring periods are displayed in the insertion to the graph.

the background counting in the same energy range.

Preliminary analysis of the results was carried out by means of comparing counting rates in two above measurement periods, each of a total duration ~ 4000 min for ten cycles. A certain excess (at a level about 1-2 RMS deviation) of the counting rate in the region of $E_\gamma = 511$ keV was observed in the first period as compared to the second one, i.e. to the background. We emphasize that the above excess was non-stationary. Time dependence of the non-stationary process approximately corresponded to the half-life of ^{18}F. Under the assumption that the observed non-stationary component of the effect is associated with the accumulation and decay of the nuclei ^{18}F, our estimate for the efficient half-life of the water molecule with respect to the nuclear channel under consideration is $T_{1/2} \sim 10^{18}$ years.

Although the total statistics was not sufficient to make a decisive conclusion, the results obtained are rather encouraging for further experiments in this intriguing direction with new more sensitive approaches. More attention should be paid to analysis of population rates of suitable molecular states under the experimental conditions. Also some further theoretical consideration are desirable regarding the fusion probability estimates for this and other molecular systems.

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ELSEVIER

Search for nuclear reactions in water molecules

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Abstract

The possibility of molecular-nuclear transitions to occur was recently predicted for some few-atomic systems. Among others, the molecule of ordinary water was shown to be a candidate for this effect due to a presence of $(1^-, 4.522$ MeV)-resonance in the ^{18}Ne nucleus. The search for traces of nuclear reactions was carried out for condensed and vaporous phases of water, with the use of low-background annihilation spectrometry. The measurements were carried out under conventional conditions and under conditions of the Baksan Neutrino Observatory. © 2001 Elsevier Science B.V. All rights reserved.

A detailed consideration of light nuclei spectra reveals numerous cases when nuclear resonance states coincide in energy with a threshold for their decay via two- or three-body channels. Provided products of the decay produce a chemically-bound system (a molecule or a radical), it is reasonable to speak of a degeneracy of these molecular and nuclear quantum states.

In the general case, a coupling between molecular and nuclear states in a few-atomic system is extremely weak due to a wide Coulomb barrier and a short-range character of nuclear forces. However, the existence of a narrow near-threshold resonance can alter the situation. Under certain condition, large distances may give a non-negligible contribution to an overlap integral of individual wave functions corresponding to pure nuclear or molecular states of such a few-atomic system. Hence, one could expect an effect of molecular-nuclear transition (MNT) in this type of compounds [1–3].

The most interesting example of such systems is the water molecule H_2O. Indeed, let us consider the system consisting of ten electrons, ten protons, and eight neutrons. These constituents can produce a water molecule or a neon atom with ^{18}Ne nucleus. Now, let us excite nucleus inside the Ne atom into a resonance state $(4.522, 1^-)$. This state, as one can see from Fig. 1 [4], has the same energy (within

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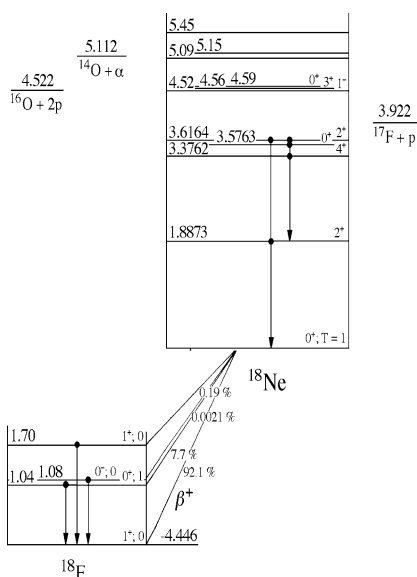belyaev@physik.uni-bonn.de (V.B. Belyaev).

Fig. 1. Fragment of the nuclear level scheme of the ^{18}Ne.

Fig. 2. Scheme of the experimental procedure.

the accuracy of experimental measurements) as the energy of threshold for decay of this state into channel $2p + ^{16}O$, which we associate with the energy of the water molecule. [1]

Now, if we take the water molecule in a rotational state 1^-, both nuclear and molecular states can be considered as degenerate states, since they are described by eigenfunctions of the same Hamiltonian, and have the same energy. Such a degeneracy means that the physical (1^-)-state of the water molecule should be a mixture of "pure" states, the nuclear and molecular ones. The nuclear state has other decay channels and one can try to register products of their decay.

It is clear that a probability of the decay of the water molecule H_2O into the resonance state of ^{18}Ne nucleus can be characterized by an overlap integral of wave functions of molecular and resonance states. In the frame of simple models for above states, which particularly take into account the Coulomb repulsion in $p + p + ^{16}O$ system at small distances (in water molecule), the overlap integral has been estimated in [1,2]. The results of these calculations show that one can expect essential enhancement of the probability

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[1] Actually, the water molecule has the binding energy around few eV, which can be, of course, neglected in the above discussion.
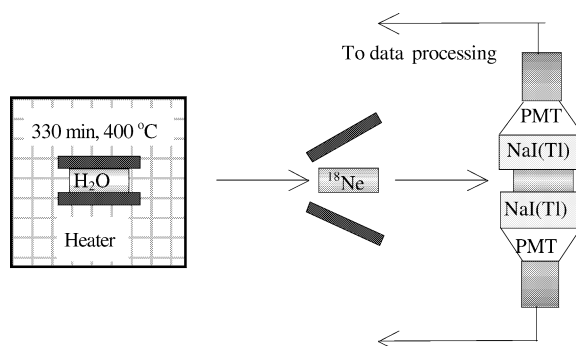
of the above transition in comparison to the transition into non-resonant (localized) states.

For the first experimental study in this direction a chain of transitions H_2O ($\equiv 2p + ^{16}O$) $\rightarrow ^{18}$Ne $\rightarrow ^{18}$F $\rightarrow ^{18}$O was considered. An experimental approach was designed to take into account specific molecular-spectroscopy properties of water. Rotational states can be excited only in free water molecules, while their population in the condensed state is prohibited due to the powerful hydrogen bonding between the molecules [5]. This gives an opportunity to control the suggested MNT process by means of interchanging conditions for accumulation or decay of the radioactive products of MNT. A simplified scheme of the experiment is shown in Fig. 2.

During the periods of accumulation, a water sample within a sealed out measuring chamber was heated up to a critical point of 647 K, at which temperature the entire amount of water was safely in a vapor phase. To withstand rather high pressure developed ($\sim$22.5 MPa), the chamber (a shortened stainless or titanium cylinder with thin membranes, transparent for the expected radiation, on the faces) was strengthened for the heating periods by thick removable caps on its faces. For the measuring periods the caps were removed, and after cooling, the chamber was placed between two large NaI(Tl)-scincillators, operating in a coincidence mode.

The experiments were carried out at the Baksan Neutrino Observatory of the Institute for Nuclear Research of the Russian Academy of Sciences. Great care was taken to reduce the background radiation as much as possible. The cosmic muons were subdued due to power shielding, as the measuring room was
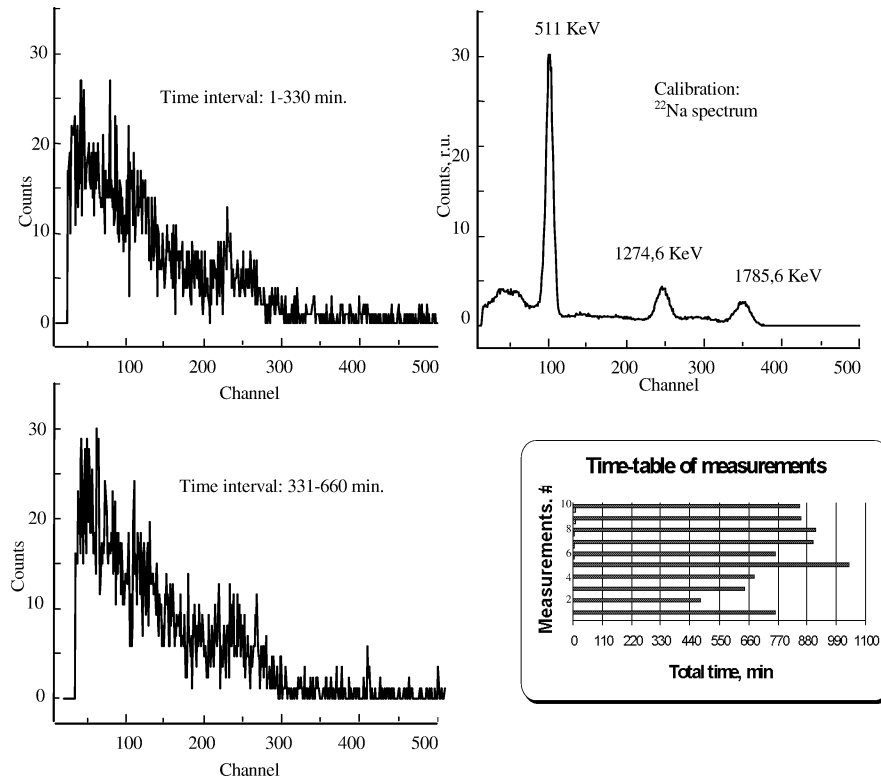
Fig. 3. Spectra of $\gamma\gamma$-coincidences in the first (upper left) and second (below) time-intervals. To the right: the ^{22}Na spectrum. At the insert there is a time diagram of measurement runs.

located in an inside gallery within the mountain Andyrchi near the Elbrus where a rock-layer thickness amounted to ~600 m of water equivalent. Interior walls, ceiling, and floor were constructed of special uranium-free concrete, while the scintillators were kept deep underground for a long time, thus short-lived cosmic-ray-induced activities were reduced to minimum.

Annihilation γ-emission with $E_\gamma = 511$ keV and a half-life ~110 min was searched for as an evidence of the presence of the accumulated nuclide ^{18}F in the measured sample. This nuclide was expected to be a daughter product of the assumed decay $H_2O \rightarrow {}^{18}Ne^*(4.522, 1^-) \rightarrow {}^{18}Ne_{g.s.}$ (β^+, 1.67 s) $\rightarrow {}^{18}F$ (β^+, 109.6 min) $\rightarrow {}^{18}O$.

For each $\gamma\gamma$-coincidence event the time was registered with an accuracy of 1.0 s, that is, a resolution was quite sufficient for a detailed analysis of a temporal dynamics in the range of interest in this experiment.

The accumulation-measuring runs were carried out repeatedly, with the accumulation interval of about three half-lives of ^{18}F, i.e., ~5.5 hours. The schedule for these runs is shown in the insert in Fig. 3. All initial intervals (the first ones after the end of heating) of every run (of about four half-lives of ^{18}F, i.e., ~440 min each), were considered as time periods contributing to the counting in the region of $E_\gamma = 511$ keV owing to the decay of the hypothetically accumulated ^{18}F. Remaining parts of measuring cycles were used to estimate the background in the same energy range.

In Fig. 3, spectra of the $\gamma\gamma$-coincidences are displayed, accumulated in two time intervals following each other and corresponding to the initial and subsequent three half-life periods of ^{18}F. The spectra were summed over the nine measuring runs (the run #2 was too short and was not included into the spectra in Fig. 3). These spectra illustrate the situation that is encountered in processing of the data. No distinct

peak is observed in the spectra. The interval of channels corresponding to the region of interest (around $E_\gamma = 511$ keV) had to be determined using a calibration spectrum measured with the ^{22}Na source which is displayed in the same picture. The above interval was chosen at 90% level of a maximum of 511 keV peak.

The coarse-pitch time distribution of the registered events centered at $E_\gamma = 511$ keV is shown in Table 1. In the fifth column of Table 1, the number of counts (the background counts subtracted) is presented in four successive time intervals equal to the half-life of ^{18}F. From the presented numbers, in the selected time interval (see Table 1) one can observe an indication on a non-stationary process in the counting rate. Variation time for the above process is of the order of the half-life of ^{18}F, the intermediary product of the decay chain $H_2O \rightarrow {}^{18}Ne \rightarrow {}^{18}F \rightarrow {}^{18}O$.

Assuming that this non-stationary part of counting is associated with the decay of ^{18}F, which was being accumulated during the heating periods of the water sample, one can estimate the effective half-life of the MNT process in water under conditions of the experiment. To this end the known expression for the decay of a system of two genetically connected radionuclides was implemented corresponding to the case when mother activity (the water molecule in our case) has a much greater half-life than a period of measurement of the decay of daughter activity:

$$T_{H_2O} = T_F\, R\, \frac{\epsilon_{\gamma\gamma}}{N_{\gamma\gamma}}\, M_{H_2O}\, N_A \left[1 - \exp(-\lambda_F t_{acc})\right]$$
$$\times \left[1 - \exp(-\lambda_F t_{msr})\right] \exp(-\lambda_F t_{del}).$$

Here, T_{H_2O} is the effective half-life of the MNT process in water, T_F the half-life of ^{18}F ($\sim$110 min), M_{H_2O} the water amount (in moles) in the sample ($\sim$3.3), $N_A = 6.023 \times 10^{23}$ (the Avogadro number), λ_F the decay constant of ^{18}F, t_{acc} the averaged accumulation (heating) time (330 min), t_{msr} the averaged counting time (440 min), t_{del} the average time-delay between the end accumulation of ^{18}F and the beginning of measurement (15 min), $\epsilon_{\gamma\gamma}$ the efficiency of $\gamma\gamma$-coincidence registration ($\sim$6%), $N_{\gamma\gamma}$ the total number of $\gamma\gamma$-coincidence counts presumably related to the decay of ^{18}F, and R the total number of the accumulation-measuring cycles (10).

Table 1

#	Measuring interval [begin, end], min	Number of $\gamma\gamma$-coincidences ($E = 511$ keV)		
		Total	Minus background, CL 68%	
1	[1, 110]	50 ± 7.1	10.6 ± 7.9	27 ± 19[b]
2	[111, 220]	49 ± 7.0	9.6 ± 7.8	
3	[221, 330]	46 ± 6.8	$\leqslant 11.7$	
4	[331, 440]	39 ± 6.2	$\leqslant 6.7$	
5	>440	39.4 ± 3.5[a]		

Notes: the data for the last two time-intervals was processed with the use of Bayes algorithm modified to account statistics of the background based on Poisson statistics [5]; for the first two intervals Gaussian approximation was used.
[a] Normalized to 110 min interval.
[b] Summed over four time intervals.

The analysis of the data results in a value $\sim 7 \times 10^{18}$ years for the lower limit of a half-life for the decay of water molecules through the studied process of MNT. It should be noted that the above value is related to the specific condition the water was under in the experiment (the phase of state, temperature, pressure, density of vapor, etc.).

A yield of MNT in the condensed state of water (suppressed from the theoretical point of view) was also measured. This part of the experiments was carried out in the conventional ("elevated") lab at the Institute of Physics and Technology Problems (Dubna). In this case, the background was measured with a sample containing heavy water (D_2O), where the necessary conditions for MNT were not fulfilled. Thus, the background was measured under the conditions (registration geometry, water amount, γ-ray absorption, etc.) identical to those under which the effect in the condensed state of H_2O was measured. For the value of the half-life of water in condensed state with respect to the $H_2O \rightarrow {}^{18}Ne$ decay, the lower limit was estimated as $\sim 4 \times 10^{21}$ years (with the 99% confidence level).

The total statistics was insufficient for a decisive conclusion. In the future it will be interesting to increase the statistics in "water" experiments and carry out experiments with molecules of other chemical compounds, which satisfy the condition of proximity of composite–nuclear resonance state to the corresponding threshold.

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Can Water "Burn"?

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Nuclear states whose energy is close (in nuclear scale) to the threshold of their production usually have large spatial sizes. This occurs due to "long" tails of wave functions expressed in terms of corresponding variables. For example, the ground state of the ^{8}B nuclei, which are the main source of high-energy solar neutrinos [1], differs from the threshold of the two-particle channel p + ^{7}Be by only 130 KeV. This fact leads to the necessity of integrating in the transition matrix elements of the reaction p + ^{7}Be $\rightarrow$ ^{8}B + γ over the region up to 300 fm [2].

In a number of cases, the existence of the near-threshold nuclear resonance leads to a considerable increase in the probability of the transition into this state as compared to the transition into the first localized state. A good example of such a situation is the nuclear transition in the $dt\mu$ mesomolecule, namely,

$$d + t \rightarrow {}^5He(3/2^+) \rightarrow {}^4He + n,$$
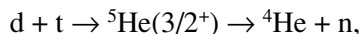
where the difference between the threshold (in the $d + t$ channel) and resonance energies is 50 KeV. As is well known [5–8], the probability of this transition exceeds, by at least four orders of magnitude, those for $dd\mu$ or $pd\mu$ molecules, where nuclear resonances are absent.

We now discuss the spectrum of states for the ^{18}Ne nucleus [3, 4]. As follows from the diagram of nuclear levels presented in the figure, the energy of the state 4.522 MeV, for the ^{18}Ne (1$^-$) nucleus within the accuracy of measurements coincides with the threshold energy of the three-particle channel p + p + ^{16}O. Since the coupling energy of the H$_2$O molecule is several electronvolts, we may ascertain that, with high accuracy, the rotational state 1$^-$ for the molecule of water and the 1$^-$ state for the ^{18}Ne nucleus are degenerated in energy, and the actual physical state characterized by these quantum numbers is a superposition of the molecular and nuclear states. In other words, in the 1$^-$ state, the wave function of a molecule of water always contains a certain admixture of the 1$^-$ state of

the ^{18}Ne nucleus. Evidently, the mixing factor is given by the integral of overlapping between pure states. This is the integral that determines the nuclear-transition probability in the H$_2$O molecule. Below, we show that the probability of the nuclear transition is not suppressed by the usual Coulomb factor due to the closeness of the threshold and resonance energies [9]. This conclusion follows from the dominant contribution of intermediate and long (in nuclear scale) distances to the overlap integral.

We now determine the wave functions of pure states. We make use of the expression

$$\psi_{mol}(X) = \frac{1}{N_{mol}} \frac{F_{5/2}(\eta_0, \kappa\rho)}{\rho^{5/2}} e^{-\kappa\rho} Y_{l\lambda}^{1M}(\hat{x}, \hat{y}) \qquad (1)$$

as a wave function of the molecule of water. Here, x and y are Jacobi variables for the system p + p + ^{16}O, $X = \{x, y\}$; $\rho = \sqrt{x^2 + y^2}$ is the hyperradius, F_ν is the regular solution to the Schrödinger equation with the Coulomb potential taken into account, $\kappa \sim \sqrt{|\varepsilon_{mol}|}$, ε_{mol} is the coupling energy for the H$_2$O molecule, $Y_{l\lambda}^{JM}(\hat{x}, \hat{y})$ is the angular function for the three-particle system having the angular momentum J; N_{mol} is the normalization factor. Finally, η_0 is the Sommerfeld parameter,

$$\eta_0 = \frac{\nu_0}{2\kappa},$$

where ν_0 is the mean value of the angular part

$$\nu(\Omega) = \frac{1}{\rho} v(X)$$

of the total Coulomb potential $v(X)$ in the system ^{16}O + p + p for $|X| = \rho$. Expression (1) adequately takes into account both the Coulomb repulsion at small distances between the particles and geometric dimensions of the system.

To describe the resonance nuclear state of the three-particle system, we make use of the Coulomb distorted spherical wave [10] normalized to the volume of this nucleus. Such a normalization condition reflects the nuclear nature of this state. Thus, we consider the

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following wave function for the 1^- state of the ^{18}Ne nucleus:

$$\psi_{res}(X) = \frac{1}{N_{res}} \frac{f^1(\rho, \omega)}{\rho^{5/2}} Y_{l\lambda}^{1M}(\hat{x}, \hat{y}), \qquad (2)$$

where $\omega = \arctan\frac{|y|}{|x|}$ is the hyperangle, and

$$f^J(\rho, \omega) = \int d\hat{x} d\hat{y}$$

$$\times \exp\left\{i K\rho - i\frac{\nu(\Omega)}{2K}\ln(2K\rho)\right\} Y_{l\lambda}^{JM}(\hat{x}, \hat{y}). \qquad (3)$$

Here, $K \sim \sqrt{E}$, where E is the energy of diverging particles in the system ^{16}O + p + p.

Using expressions (1) and (2), we find that the overlap integral I is

$$I = \int dX \psi_{res}(X) \psi_{mol}(X)$$

$$\sim \exp\left\{-\frac{\pi}{2}\eta_K^0\right\} \exp\{i\eta_K^0 S(\sigma, \xi)\}, \qquad (4)$$

where $\eta_K^0 = \dfrac{\nu(\Omega_0)}{2K}$ is the generalized Sommerfeld parameter corresponding to the point Ω_0 of the minimum for the function $\nu(\Omega)$, while $\xi = \dfrac{K}{\kappa}$ and $\sigma = \dfrac{\nu(\Omega_0)}{\nu_0}$. According to its definition, the variable σ varies within the limits $0 < \sigma < 1$. The variation of the second parameter ξ is caused by the nonzero width of the 4.522 MeV (1^-) level of the ^{18}Ne nucleus. According to the definition of this parameter, it can vary within the range

$$0 \le \xi \le \sqrt{\frac{\Gamma_{2p}}{|\varepsilon_{mol}|}},$$

where Γ_{2p} is the decay width of the nuclear resonance into the channel ^{16}O + p + p. The numerical investigation of the function $S(\sigma, \xi)$ demonstrates the existence of the subregion of parameters σ and ξ, for which $\text{Im}S < 0$ and, simultaneously, $|\text{Im}S| > \pi/2$. Thus, the overlap integral (4) and the velocity W of the transition $H_2O \rightarrow {}^{18}$Ne (1^-) into the resonance state of the ^{18}Ne nucleus, which is defined by the expression

$$W = \kappa c |I|^2, \qquad (5)$$

exponentially increases with decreasing K (at low energies E) in contrast to the probability of the transition into localized nuclear states. Such behavior of the velocity of the transition is explained by the contribution into inte-
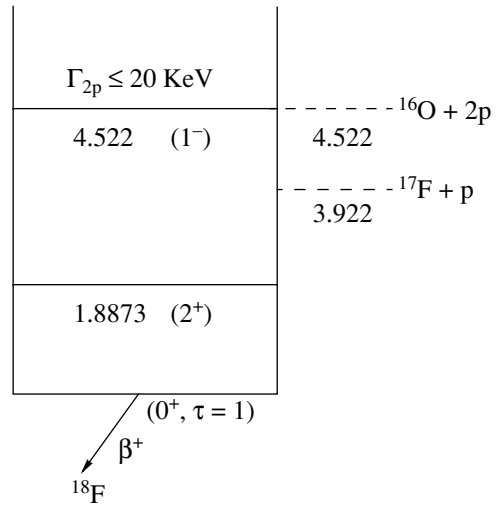
Fragment of the spectrum for states of the ^{18}Ne nucleus.

gral (4) from the region of intermediate and large distances between the particles.

Thus, it follows from (4) that water must gradually transform from the molecular state into the excited state of the ^{18}Ne nucleus. The latter one, in its turn, will decay into either the channel

$$^{17}\text{F} + \text{p} + Q_1, \quad Q_1 \simeq 0.6 \text{ MeV},$$

or according to the chain ^{18}Ne $(1^-) \rightarrow {}^{18}$Ne $+ \gamma + Q_2 \rightarrow {}^{18}$F $+ e^+ + \nu$, $Q_2 \simeq 4.522$ MeV.

We now discuss possible modifications of the wave functions (1) and (2) as well as their effect on the overlap integral (4).

The internal structure of a molecule of water (for example, the fixed angle between the directions from the oxygen nucleus to the protons) could be taken into account more adequately when multiplying (1) by an appropriate polynomial of variables ρ and ω. However, as follows from the derivation of the asymptotic formula (4), this leads only to exponential (in terms of η_0) corrections to the asymptotic formula (4) but does not affect its exponential behavior.

In essence, the modification of expression (2) for the wave function of the nuclear resonance should be performed only in the region of small distances between the ^{16}O nucleus and protons. It is clear that any such modification can lead to only exponentially small corrections to the result (4).

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