Search for metastable states of nuclei on the basis of delayed proton emission

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A search was made for metastable states of nuclei with excitation energy of several MeV per nucleon. Such nuclei could be density isomers (superdense nuclei), shape isomers, or formed by some other mechanism. The experiment was performed with a beam of oxygen nuclei (1 GeV/nucleon) and a lead target. Protons of energy from 5 to 25 MeV, which might have been emitted upon transition of the nucleus from the metastable to the normal state, were recorded. It was established that the probability of formation of metastable states of nuclei in inelastic OPb interactions does not exceed $\sim 10^{-6}$ (at a lifetime 10^{-7}–1 s) and $\sim 10^{-7}$ (at a lifetime 1–10^5 s).

Interest in a question raised in 1946,[1] that of existence of nuclear density isomers, and particularly of superdense nuclei, became particularly interesting following publication of a paper by Migdal,[2] in which the specific mechanism (formation of a pion condensate) that might lead to the existence of such objects was indicated. A number of additional mechanisms that make possible the existence of nuclear density or shape isomers were subsequently proposed (see, e.g., Refs. 3–6). Among the rather large group of experiments, differing greatly in the principle underlying the search for isomer states of nuclei and in the procedure used, we shall discuss only the experiment of Karnaukhov's group,[7] to which our experiment is quite close. The authors of Refs. 7 searched for nuclei in a metastable state, as manifested by multiple delayed-neutron emission accompanying the transition of the nucleus from a metastable to the ground state. In our experiments we attempted to record such a transition as revealed by multiple emission of protons. If protons are recorded, the search can include metastable states with lifetimes $\tau \gtrsim 10^7$ s (as against $\tau \gtrsim 1$ s in Ref. 7).

The experiment was performed on an extracted beam of oxygen nuclei (energy 1 GeV) from the proton synchrotron of High-Energy Laboratory of our Institute. The advantage of nuclear beams in experiments aimed at finding density isomers is that the expected condensation of the nuclear matter by nucleus-nucleus collisions is expected to be much greater (see, e.g., Ref. 8) than in proton-nucleus interactions.

RECORDING APPARATUS

The principal recording element of the apparatus consisted of eight scintillation counters, with scintillators based on polystyrene, symmetrically placed around a lead target ($20\times40\times0.2$ mm). The scintillators were disks 50 mm in diameter and 1 mm thick. The distance from the center of the target to the centers of the scintillators was 42 mm. All counters were checked for homogeneity (independence of the signal amplitude on the leading point of the particle in the scintillator) and for energy resolution. The scintillators used were also specially investigated[9] to determine the dependence of the light yield on the ionization density. Some results of the investigation of the characteristics of the counters used in the experiment are given also in Ref. 10.

Figure 1 shows the ratio of the average amplitude A_p of signals from protons of energy E_p to the average amplitude A_β from a fast (~ 1 MeV) electron passing through a scintillator 1 mm thick in a direction perpendicular to the surface. It can be seen that in the proton energy interval from 5 to 25 MeV the ratio of the indicated amplitudes is $\geqslant 10$. The discriminator thresholds were set at a level 7.5 times higher than the amplitude of the signal from an electron incident perpendicularly on the scintillator. With account taken of the energy resolution and of the homogeneity of the counters, this ensures that protons entering the scintillators and having energies from 5 to 25 MeV are recorded, with 100% efficiency, while the electron-recording efficiency is drastically suppressed (by approximately three orders of magnitude). The amplitude stability was monitored by α sources (of area ≈ 2 mm^2) glued to all working scintillators. Owing to the dependence of the scintillator light output on the ionization density, the signals from the α particles were approximately 4 times lower than the threshold of the electronic recording circuitry and produced therefore no background. The signals from the discriminator output were fed to a majority coincidence circuit with resolution time 10 nsec. The number of coincidences with multiplicity $n\geqslant3$ and $m\geqslant4$ were recorded, and for control purposes also with $n\geqslant1$ and $n\geqslant2$.

In the search for nuclear states with lifetimes from $\sim 10^{-7}$ to ~ 1 s the equipment was operated in a regime

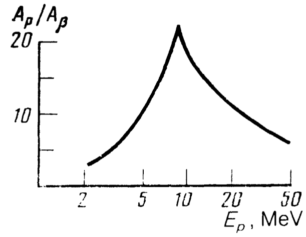

FIG. 1. Ratio of average amplitudes of signals from protons of energy E and from electrons of energy ~ 1 MeV perpendicularly incident on a scintillator 1 mm thick.

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hereafter called for brevity the "regime between bunches." The extracted beam has a microstructure due to the fact that the particles in the accelerator rings are bunched. The time interval between bunches is 400 ns (for accelerated-nucleus energy 1 GeV/nucleon) and the bunch FWHM is ~ 40 nsec.[11] Therefore in our regime between bunches the apparatus was blocked for 260 ns during time of passage of the particle bunch, and the "live" time was consequently about one-third the total time.

The second regime—"between cycles"—was used to search for decays of metastable states of nuclei having lifetimes from ~ 1 to $\sim 10^5$ s. The apparatus was blocked (~ 1 s) during the time of beam passage, and unblocked in the interval between cycles (~ 8 s).

EFFICIENCY OF APPARATUS

The efficiency of the apparatus, i.e., the probability of recording the decay of a certain system (this concept will be defined more precisely below) can be naturally represented as a product of a "temporal" efficiency and a "spatial" one. The temporal efficiency is the decay probability of a system with lifetime τ in a "live" time. This component of the total efficiency is determined by the information-recording time and can be easily calculated. Its dependence on the system lifetime τ is shown in Fig. 2. We discuss below the spatial efficiency, or simply efficiency for short.

By efficiency ε_K of the apparatus we mean the probability of simultaneous operation of K scintillation counters when a metastable system decays in the target. Clearly, ε_K depends essentially on the number of protons emitted during the decay and on their energy spectrum. Figure 3 shows the probability of operation of one counter vs the proton energy, calculated by statistical sampling. The proton emission point was statistically sampled uniformly over the target volume, the energy loss in the screen (a layer of optically opaque paper) was accounted for by the STOPOW program,[12] and the counter was assumed to operate if a proton of energy from 5 to 25 MeV entered the scintillator. It can be seen that starting with proton energies $\geqslant 10$ MeV the counter-operation probability is practically constant and is determined by the average solid angle.

The efficiency ε_K (we are mainly interested in $K = 3$) depends thus on the number and on the energy spectrum of the emitted protons. We used the following procedure to present the results in compact form. Assume that the nucleus goes over from the metastable to the ground state in two steps, viz., a tunnel transition that results in formation of a "usual" excited nucleus of energy E^* per nucleon, followed by decay of the excited equilibrium state.[7] The latter process can be treated within the framework of the evaporation model.

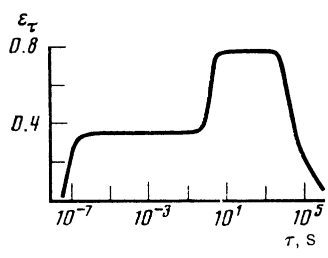

FIG. 2. Probability of recording a metastable-state decay vs lifetime τ (temporal efficiency).

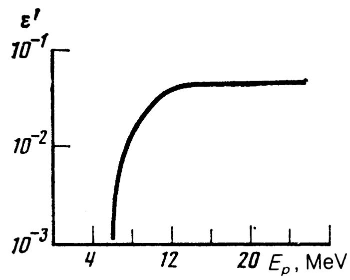

FIG. 3. Probability of recording a proton by one counter vs the proton energy.

The average multiplicity of the evaporated protons was assumed to be $\langle n_p \rangle = 1.8E^*$ and $\langle n_p \rangle = 1.3E^*$ (E^* in MeV) for nuclei with $A \sim 200$ and 100, respectively. The energy spectrum of the protons was assumed Maxwellian with temperature $T = (10E^*)^{1/2}$ (T and E^* are in MeV). The Coulomb potential V_C that shifts the Maxwell spectrum is calculated from the equation $V_C = k\eta(T)V_0$, where $V_0 = Z/R$ (Z is the nuclear charge, R is the sum of the nucleus and proton radii), the factor $k = 0.7$ takes into account the tunneling below the barrier, and $\eta(T) = (1 - T^2/T_{\rm crit})$ with $T_{\rm crit} = 9$ MeV is the dependence of the Coulomb energy on the temperature of the nucleus. The connection between E^*, $\langle n_p \rangle$, T and V_C, as well as the numerical values of the parameters k and $T_{\rm crit}$, were taken from Refs. 13 and 14. A Poisson distribution in multiplicity was assumed for the emitted protons. More accurate calculations[13] show a distribution narrower than that of Poisson, but this circumstance does not influence strongly the efficiency calculations for $E^* \geqslant 2$ MeV.

We note once more that the scheme assumed, which is in principle not important for the interpretation of the experiment, permits the efficiency ε_K to be expressed as a function of single parameter E^*.

EXPERIMENTAL RESULTS

A total of $3.7 \cdot 10^{10}$ oxygen nuclei of energy 1 GeV/nuclei passed through the apparatus during the operating time (20 h) of the beam (average intensity $5 \cdot 10^6$ nuclei per cycle). The probability of inelastic interaction of an oxygen nucleus in the target, with account taken of the cross section for inelastic interaction[15] and of the beam-intensity distribution over the target surface (at an angle 6° between the target plane and the beam) was $0.47 \cdot 10^{-2}$. Neither quadruple nor triple coincidence were recorded in the between-the-cycles regime, while the number of these coincidences in the between-the bunch regime was respectively 1 and 5. These readings may be caused[11] by the presence in the beam, at 10^6 of the total number of beam particles, of "interbunch" particles (i.e., particles "tumbling out" of the accelerated bunch). Since this source of the background cannot be correctly calculated, we increased correspondingly the lower

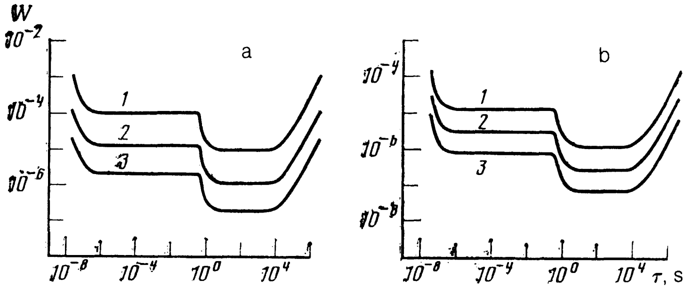

FIG. 4. Upper bound of probability of formation of metastable nuclei with $A \sim 100$ (a) and ~ 200 (b) with excitation energy E^* per nucleon and with lifetime τ in inelastic interactions between oxygen and lead nuclei: 1—$E^* = 1$ MeV, 2—2 MeV, 3—5 MeV.

bound of the probability of formation of metastable nuclear states with lifetimes 10^{-7} to 10^{-1}. The final data for the maximum probability (at a confidence level 90%) of formation of metastable states with $A \sim 200$ and 100, as a function of their lifetime τ and excitation energy E^* per nucleon, are shown in Fig. 4. The boundaries shown were calculated using the recorded number of triple coincidences.

It is also of interest to estimate the probability of formation of relatively light density isomers ($A \sim 20$–40). The existence of metastable states of light nuclei, of density 15–30 times lower than that of ordinary nuclei and with excitation energy 5–10 MeV per nucleon, is postulated in Refs. 5 and 6. If such super-rarefied nuclei were to exist, they could explain the anomalous increase of the cross sections for inelastic interaction of fast fragments ("anomalons," see the review by Karmanov[16] and the references therein). It is quite natural to assume that in our formulation of the experiment such super-rarefied nuclei could also be produced via fragmentation of the target nucleus. The question of the efficiency with which their decays (on going from the metastable to the ground state) are recorded is rather complicated, since the evaporation model is inapplicable to light nuclei.[13] On the basis of the published data one can expect a probability not less than 0.1 for emission of three protons with energies $\geqslant 8$ MeV from nuclei with $A \sim 20$–40 and excitation energies 5–10 per nucleon. The experimental data allow us to state that the efficiency of formation of super-rarefield nuclei with the indicated characteristics in OPb inelastic interactions does not exceed $4 \cdot 10^{-6}$ and $3 \cdot 10^{-7}$ at lifetimes $4 \cdot 10^{-8} < \tau < 4 \cdot 10^{-1}$ s and $4 \cdot 10^{-1} < \tau < 4 \cdot 10^{5}$ s, respectively. To explain the anomalons, much higher (by several orders) metastable-nucleus formation probabilities are necessary.

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