Search for unstable superdense nuclei

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During bombardment of a lead target by a beam of relativistic ^{12}C nuclei we carried out a search for radioactive superdense nuclei having lifetimes in the range 10^{-8}–10^{-1} sec. We have shown that the probability of production of a nucleus having a lifetime in the range 10^{-8}–10^{-6} sec and decaying with emission of an energetic electron or positron ($E > 45$ MeV) does not exceed $\sim 3 \cdot 10^{-4}$ in the inelastic CPb interaction, and the probability of production of a nucleus having a lifetime in the range 10^{-7}–10^{-1} sec and decaying with emission of a neutral pion does not exceed $\sim 6 \cdot 10^{-4}$ in the inelastic CPb interaction.

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1. INTRODUCTION

The possibility of existence of superdense nuclei began to be discussed extensively after the work of A. B. Migdal (see his book[1] and references therein) on formation of a pion condensate. Attempts to observe superdense nuclei experimentally have been made repeatedly (a review of the experiments carried out up to 1977 can be found in Ref. 2). One area of search was proposed and carried out in 1976 by Kulikov and Pontecorvo.[3] These authors gave an upper limit for the cross section for production of radioactive superdense nuclei by a proton beam in a lead target. The apparatus was sensitive to lifetimes $\tau \gtrsim 5 \cdot 10^{-3}$ sec and electron or positron energies $E_e > 45$ MeV. As the authors of Ref. 3 note, the approximate relation between the lifetime τ and the β-decay end-point energy $E_{\rm lim}$ expressed by the formula $\tau \sim E_{\rm lim}^{-5}$ (Ref. 4) leads for $\tau \sim 10^{-3}$ sec to values $E_{\rm lim} \sim 20$ MeV, which makes it extremely desirable to reduce the energy threshold for detection of the electrons. This step was taken in the work of Yu. A. Troyan and his colleagues.[5,6] The technique used by them permitted detection of decay particles of practically any energy and in addition they looked for superdense states of nuclei in bombardment of targets by relativistic nuclei. Nuclear beams are promising for solution of this problem since, in the words of Kulikov and Pontecorvo,[3] "the appearance of shock waves capable of providing sufficient compression of nuclear matter appears more probable in collisions of two heavy nuclei than in collisions of nucleons with nuclei." However the technique used in Refs. 5 and 6 did not permit an advance to the lifetime region $\tau \lesssim 10^{-3}$ sec.

In the case in which metastable superdense nuclei[7] are produced in nuclear interactions, they might be observed by the delayed emission of nucleons, and a search for delayed nucleons in the region of lifetimes of metastable states $\tau \gtrsim 1$ sec was undertaken by Karnaukhov and his colleagues.[8]

In this article we shall briefly describe a measurement technique and present experimental data obtained on the upper limits of the cross section for production of superdense nuclei unstable against β decay in the range of lifetimes $10^{-8} \lesssim \tau \lesssim 10^{-6}$ sec, and also upper limits of the cross sections for production of metastable superdense nuclei which decay with emission of a π^0 meson (this possibility was brought to our attention by I. N. Mishustin) and which have lifetimes in the range 10^{-7}–10^{-1} sec.

The experiment was carried out in an external beam of carbon nuclei (momentum 4.5 GeV/c per nucleon and 1.68 GeV/c per nucleon) at the JINR proton synchrotron.

2. METHOD OF MEASUREMENT

a) β-active nuclei

The experimental setup is shown in Fig. 1a. Scintillation counter S_1 was used to count the number of nuclei (^{12}C with momentum 4.5 GeV/c per nucleon) in the beam and to obtain a time marker for the arrival of a nucleus at the target. Beginning at a time $\tau_1 = 50$ nsec after the time marker and for a period of time $\tau_2 = 50$ nsec, counters S_3–S_6 connected in coincidence recorded particles emitted from the target. If counter S_2 operated during the time τ_2 (the next beam particle) the coincidence count $S_3 \times S_4 \times S_5 \times S_6$ was blocked. The beam intensity was chosen such that the fraction of blocked time gates τ_2 was about 10%. Measurements were made with a target of lead of thickness 5mm located at an angle 45° to the beam. Absorbers ϕ_1 and ϕ_2 consisting of Plexiglas and aluminum were chosen so as to record electrons with energy $E \gtrsim 45$ MeV.

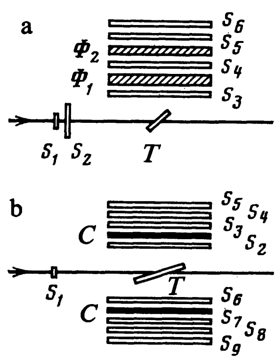

FIG. 1. Arrangement of apparatus. T is the target, S_1–S_9 are scintillation counters, Φ_1 and Φ_2 are absorbers, and C are converters.

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b) π^0 – active nuclei

The measurement setup for these nuclei is shown in Fig. 1b. Counter S_1 counts the number of nuclei (^{12}C with momentum 1.68 GeV/c per nucleon) incident on the target. A coincidence count $\overline{S}_2\times S_3\times S_4\times S_5\times\overline{S}_6\times S_7\times S_8\times S_9$ corresponds to decay of a π^0 meson in the target into two γ rays. Here the γ rays should leave the target T (5mm of lead at an angle 20° to the beam) without conversion and be converted in the lead converters C (thickness 5mm each). The method of searching for delayed decays of nuclei in the target is based on the fact that the beam extracted from the synchrotron has a time structure due to the time of revolution of the beam in the accelerator ring. The time between the bunches is constant and amounts to 400 nsec (for a ^{12}C beam momentum 1.68 GeV/c per nucleon), while the total width of the bunch at half height is 30–40 nsec. Therefore the signal allowing recording of the number of operations of counters S_2–S_9 was given at a time $\tau_1 = 125$ nsec after the center of the bunch and had a duration $\tau_2 = 150$ nsec.

3. EXPERIMENTAL RESULTS

Upper limits of the cross sections for production of superdense nuclei obtained in our experiment are given in Fig. 2. Curve 4 gives the upper limit (confidence level 90%) on the cross section for production of superdense nuclei having a lifetime τ and decaying with emission of an electron or positron with energy $E \gtrsim 45$ MeV, in a beam of carbon nuclei with momentum 4.5 GeV/c per nucleon in a lead target. Curve 5 gives the upper limit (also at the 90% confidence level) on the cross section for production of nuclei unstable against emission of a π^0 meson with a lifetime τ, by carbon nuclei with momentum 1.68 GeV/c per nucleon in a lead target. In the same figure we have also shown the results of Ref. 6 (curves 1, 2, and 3).

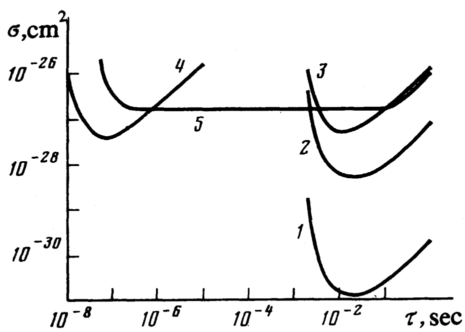

FIG. 2. Upper limits of the cross sections for production of superdense nuclei: curves 1, 2, and 3 are for nuclei produced in pPb, HePb, and CPb interactions and decaying with emission of an electron or positron with $E > 17$ MeV.[6] Curve 4 is for CPb interactions with emission of an electron or positron with $E \gtrsim 45$ MeV. Curve 5 is for CPb interactions with emission of a π_0 meson with energy about 50 MeV.

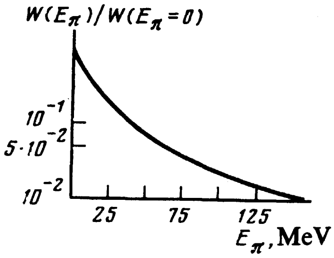

FIG. 3. Relative probability of detection of a π_0 meson as a function of its kinetic energy.

In determining the upper limits shown, we took into account the geometrical efficiencies of the detecting systems, the probabilities of conversion of the γ rays (for the π^0 - unstable nuclei), and the dependence of the efficiency for detection of a decay on the lifetime τ of the decaying object, which is given by the expressions

$$W=e^{-\tau_1/\tau}(1-e^{-\tau_2/\tau}), \quad (1)$$

$$W=e^{-\tau_1/\tau}(1-e^{-\tau_2/\tau})(1-e^{-T/\tau})^{-1} \quad (2)$$

respectively for cases a) and b) of the preceding section. Equation (2) is valid for lifetimes τ less than the total duration of the beam spill in the acceleration cycle (about 0.4 sec), i.e., up to about 0.1 sec. The efficiency for detection of a π^0 meson will depend substantially on its energy. Calculated values of this dependence are given in Fig. 3. Curve 5 in Fig. 2 corresponds to a π^0 – meson kinetic energy ~50 MeV. At lower π^0 – meson energies the efficiency for their detection increases and consequently a more restrictive upper limit is obtained than that in Fig. 2.

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