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Search for spontaneous transition of nuclei to a superdense state

R. Bernabei[1,2,a], P. Belli[1,2], F. Cappella[1,2], F. Montecchia[1,2,b], F. Nozzoli[1,2], A. d'Angelo[3,4,c], A. Incicchitti[3,4], D. Prosperi[3,4], R. Cerulli[5], C.J. Dai[6], H.H. Kuang[6], J.M. Ma[6], and Z.P. Ye[6,d]

[1] Dipartimento di Fisica, Università di Roma "Tor Vergata", Rome, Italy
[2] INFN, Sezione di Roma2, I-00133 Rome, Italy
[3] Dipartimento di Fisica, Università di Roma "La Sapienza", Rome, Italy
[4] INFN, Sezione di Roma, I-00185 Rome, Italy
[5] INFN - Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy
[6] IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, PRC

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Abstract. We report the results of an experimental search for spontaneous transition of nuclei from ordinary to superdense state in NaI(Tl). New limits on the superdense-state parameters are presented.

PACS. 21.10.Ft Charge distribution – 21.10.-k Properties of nuclei; nuclear energy levels – 21.65.+f Nuclear matter – 29.40.Mc Scintillation detectors

1 Introduction

It is well known that all nuclei have almost the same average density ρ_0; this situation must be ascribed to the structure of nuclear forces, in particular to the existence of repulsion at short distances. As a consequence, it was argued that the energy of a nucleus as a function of its density, $E(\rho)$, must have a minimum for the normal density ρ_0. Moreover, from the very beginning of nuclear physics the possible existence of superdense nuclear states with $\rho_s > \rho_0$ was debated [1–4]. A transition to the superdense state can occur if $E(\rho)$ has a second minimum for $\rho = \rho_s$. This situation is illustrated qualitatively in fig. 1.

The possible existence of superdense states was also discussed in some pioneering works of Migdal and others [5], in connection with the so-called "pion condensation" phenomenon. More recently this argument has been developed by many authors: for example in ref. [6] it was shown that both symmetric nuclear matter ($N = Z$) and pure neutron matter ($Z = 0$) could undergo transitions to phases with pion condensation and densities of $\simeq 2\rho_0$ and $\simeq 1.3\rho_0$, respectively.

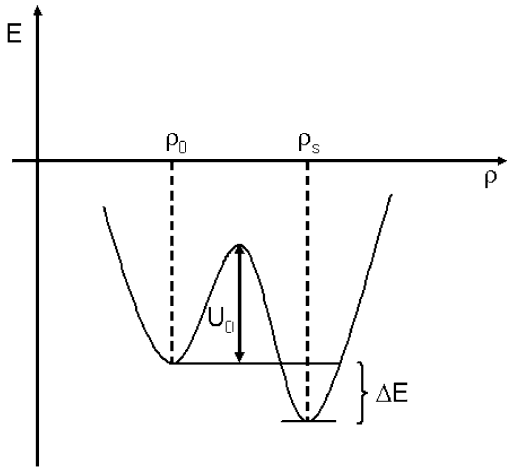

Fig. 1. Energy of the nucleus as a function of its density ρ. ΔE is the energy released in the transition $\rho_0 \rightarrow \rho_s$; U_0 is the height of the potential barrier to be overcome.

To realise the density transition $\rho_0 \rightarrow \rho_s$, a potential barrier U_0 must be overcome whose shape and height cannot be reliably predicted on the basis of actual knowledge. In this framework a nucleus (or a part of a nucleus) can be metastable and spontaneously can go over to the superdense state.

In the past several experimental works employing different techniques have been devoted to determine limits for the probability λ of the $\rho_0 \rightarrow \rho_s$ transition and for the effective height U_0 of the potential barrier [7,8]. The aim of the present work is to improve these limits. To realise

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[a] e-mail: `rita.bernabei@roma2.infn.it`

[b] Also at: Università "Campus Bio-Medico" di Roma, 00155, Rome, Italy.

[c] Also at: Scuola di Specializzazione in Fisica Sanitaria, Università di Roma "Tor Vergata", I-00133 Rome, Italy.

[d] Also at: University of Zhao Qing, Guang Dong, PRC.

this program it is needed to adopt some simple model allowing to connect U_0, λ, ρ_0 and ρ_s. In the following we will adopt the ideas developed in refs. [2,5,9] in which it was postulated that the transition can occur as a consequence of nuclear volume oscillations (hydrostatic compression). According to ref. [9] we can write the relation

$$U_0(\mathrm{MeV}) = \frac{7.2 \cdot 10^4}{A^{\frac{5}{3}}} \left(1 + \frac{1}{55} \cdot \ln \frac{\tau}{10^{20} y}\right) \cdot \left[1 - \left(\frac{\rho_0}{\rho_s}\right)^{\frac{1}{3}}\right]^{-2}, \qquad (1)$$

where $\tau = \lambda^{-1}$ is the lifetime of the process in years.

In this work an experimental approach similar to the one previously considered in ref. [10] has been exploited by searching for γ-radiation accompanying the occurrence of the searched transition in NaI(Tl). In particular, here we consider a possible transition of sodium and iodine nuclei to a superdense state releasing a ΔE larger than 10 MeV through γ radiation.

Our search has been carried out by using data collected deep underground (about 3600 m.w.e.) at the Gran Sasso National Laboratory of INFN by using the highly radiopure $\simeq$ 100 kg NaI(Tl) set-up of the DAMA experiment (DAMA/NaI). This set-up has been mainly devoted to the investigation of Dark-Matter particle in the galactic halo [11–13], but has also investigated several other rare processes [14,15]. In particular, in ref. [14] data collected in the tens MeV energy region have already been used to investigate possible spontaneous emission of protons due to violation of the Pauli exclusion principle. DAMA/NaI has completed its data taking in July 2002 and has been replaced by the new more radiopure $\simeq$ 250 kg NaI(Tl) set-up, named DAMA/LIBRA, now running.

The deeper experimental site, the much larger exposure, the effective shielding of the detectors and the strong improvements in detectors' radiopurity, occurred during about the last 30 years, allow to investigate these possible processes in NaI(Tl) with much larger sensitivity than the pioneer experiment of ref. [10].

2 Experimental result

The description of the set-up and of its main performances have been given in ref. [16]: moreover, some other information on its performances and on the upgrading occurred in 2000 have been given in refs. [12,13]. Here we only remind that the data considered here have been collected with nine 9.70 kg NaI(Tl) crystal scintillators enclosed in suitably radiopure Cu housings. Each detector has two 10 cm long tetrasil-B light guides directly coupled to the opposite sides of the bare crystal; two low background photomultipliers work in coincidence. The detectors are enclosed in a low radioactive copper box inside a low radioactive shield made of 10 cm copper and 15 cm lead. The lead is surrounded by 1.5 mm Cd foils and about 10/40 cm of polyethylene/paraffin; moreover, the installation is almost completely surrounded by about 1 m of concrete acting as a further neutron moderator. A high-purity (HP) nitrogen atmosphere is maintained inside the copper box. The passive shield is also enclosed in a sealed plexiglas box maintained in HP nitrogen atmosphere as well as the glove-box which is located on the top of the shield to allow the detectors calibration in the same running conditions without any contact with external environment. The installation is subjected to air conditioning. As of interest here, the energy, the identification of the fired crystals and the absolute time occurrence are acquired for each event.

The calibration has been performed with several gamma sources; the energy resolution in the high-energy region is typically $\frac{\sigma}{E} = \frac{0.0104}{\sqrt{E(\mathrm{MeV})}} + 0.0324$.

The data analysis has been performed by searching in an exposure of 33834 kg $\cdot$ day events with multiplicity larger than or equal to two and the total energy released in all the nine 9.7 kg NaI(Tl) used detectors is larger than 10 MeV. We found 1551 events satisfying the required features in the given exposure. These events can largely be ascribed to the background due to high-energy muons surviving the mountain shielding, nevertheless —to be on the safest side— in order to estimate the lifetime of the process, we consider the following cautious approach (widely used, *e.g.*, in the evaluation of model-dependent exclusion limits in particle Dark-Matter direct searches): the signal cannot exceed the experimental number of counts plus $n \times \sqrt{N}$ (where n gives the C.L. and N is the measured counting rate in the considered energy region)[1]. Thus, in the present case, the maximum counts that can be ascribed to the expected signal cannot exceed the value $S_{\mathrm{lim}} = 1600$ at 90% C.L.

The restriction on the lifetime of the process can be, then, obtained by using the formula:

$$\tau > \frac{N_B T \epsilon}{S_{\mathrm{lim}}}, \qquad (2)$$

where $N_B(^{23}\mathrm{Na}) = N_B(^{127}\mathrm{I}) = 4.64 \cdot 10^{26}$ atoms (note that we consider also as source four additional 7.05 kg NaI(Tl) detectors placed on the top of the nine used detectors [16], but not included in the trigger for the given measurements); T corresponds to the exposure time and is equal to 1.062 y. Finally, the mean efficiency ϵ has been calculated assuming for simplicity that the energy release occurs through a single γ quantum emission. In particular, it has been calculated as a function of the energy of the γ between 15 and 90 MeV by a Monte Carlo code and ranges between 0.22 and 0.50.

The lifetime lower limits (90% C.L.) obtained for sodium and iodine nuclei, as a function of ΔE are depicted in fig. 2 in the range 15–90 MeV. From these restrictions, applying eq. (1), one can derive lower limits for the barrier potential, U_0, as reported for the sodium and

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[1] Restrictions on the process's lifetime of about one order of magnitude larger than those obtained with this cautious procedure can be derived if these background events were subtracted.

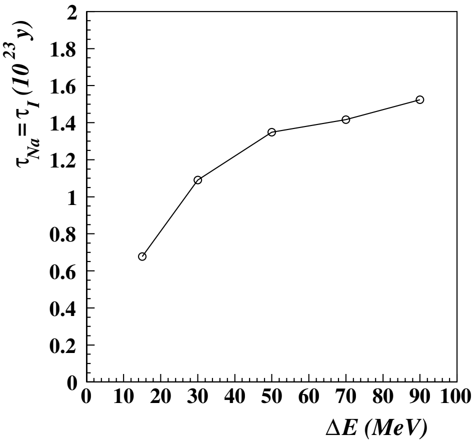

Fig. 2. Obtained lifetime lower limits (90% C.L.) on the considered process in sodium and iodine nuclei as a function of the energy release.

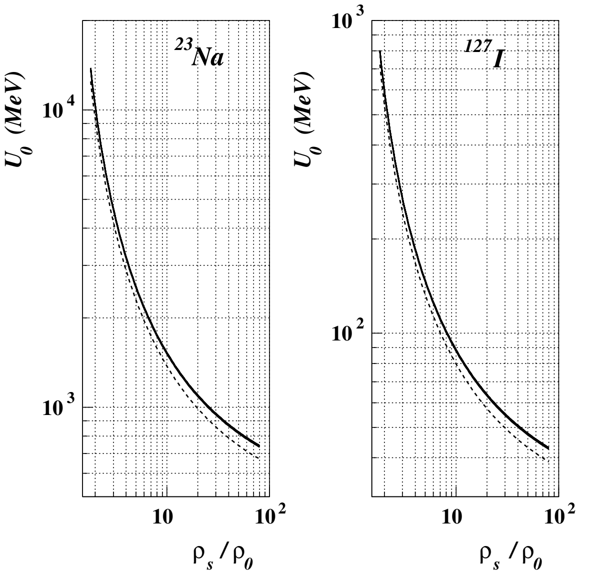

Fig. 3. Obtained lower limits (90% C.L.) on the barrier potential, U_0, for the sodium and iodine nuclei (continuous lines); the behaviours for the various energy releases ΔE are practically indistinguishable. The dashed lines are the lower limits for U_0 as calculated from the previous best limits in ref. [10]. We note that, although the restriction on τ is increased by about 3 orders of magnitude, the restriction on U_0 is also modestly increased because of the logarithmic dependence in eq. (1).

iodine nuclei in fig. 3; the behaviours for the various energy releases ΔE considered here are practically indistinguishable. In the same figure the lower limits for U_0 calculated from the previous best limits of ref. [10] ($\tau > 3 \cdot 10^{20}$ y) are also reported as dashed lines.

Although the restriction on τ is increased by about 3 orders of magnitude, the restriction on U_0 is also modestly increased because of the logarithmic dependence in eq. (1).

3 Conclusions

Thanks to the deeper experimental site, to the much larger exposure, to the effective shielding of the detectors and to the strong improvements in detectors' radiopurity, occurred during about the last 30 years, a new search for possible transitions to superdense nuclei in NaI(Tl) has been performed with much larger sensitivity than the pioneer experiment of ref. [10].

Improved limits on the superdense-state parameters have been obtained in the present experimental search for such a possible spontaneous transition. In particular, the lower limits on the lifetime of the process have been increased by about three orders of magnitude, while those on the barrier potential U_0 have also modestly been improved.

To obtain further relevant improvements in this kind of search, significant steps forward in the low-background technology and in the available exposure are necessary; some preliminary efforts are in progress.

Finally, complementary information on the existence and properties of superdense nuclear states might be inferred from searches for superdense nuclei of cosmic origin. However, mechanisms can, in principle, be considered which might disfavour either their production in those scenarios or their survival. The complexity of the topics on the superdense nuclear states is addressed, *e.g.*, in [4,5].

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