DOUBLE BETA DECAY: THE FUTURE

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ABSTRACT

The future experiments being assembled or proposed to search for Double Beta Decay are presented and discussed with peculiar focus on the searches for the neutrinoless channel. Extension to larger masses of experiments presently running with conventional detectors is considered. Special attention is devoted to new techniques, which could allow to overcome the limitation of the presently running experiments and provide an ample choice of double beta decay candidate nuclei. The potentialities of the various techniques and the expected sensitivities, as quoted by the authors by simulation or on the basis of the present performance of the running experiments are reported, compared and discussed.

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1. INTRODUCTION

The interest on searches on Double Beta Decay (DBD) and the presently running experiments have been reported and discussed, together with the obtained results, in the comprehensive review presented to this Conference by H. Ejiri [1]. Let me only remind that two neutrino DBD have been discovered, or indicated for 10 nuclei, to the ground state and also to the excited 0^{+*} state in the case of ^{100}Mo. These results are impressive: the background has been strongly reduced and some of the obtained lifetimes are the longest ever found in Nature for rare decays. It is however understandable that the main interest is towards the process of DBD where only two electrons are emitted with or without one or more majorons. These processes would in fact imply non-conservation of the lepton number and indicate a finite value for the average mass $<M_N>$ of the electron antineutrino and/or an admixture of right handed currents in the weak interaction wave function. Unfortunately the constraints on these parameters, which can be extracted from the negative results obtained so far in neutrinos DBD experiments, are affected by a considerable error (up to a factor of 3), mainly due to uncertainties in the calculation of nuclear matrix elements. The same is true for the constraint of the majoron coupling, based on the lower limit on lifetime obtained for this type of decay. I am rather disturbed, as an experimentalist, by the fact that calculation of two neutrino double beta decay, which should be more difficult, but where the effect has been found, agree better among themselves than those on the neutrinoless channel! It seems therefore to me that all nuclei that have been theoretically suggested as reasonable candidates for neutrinoless DBC should be investigated.

2. A FEW CONSIDERATIONS

As mentioned before the existence of two neutrino DBD is definitely proven, even if some disagreements are present in the geochemical measurements of the lifetime of ^{130}Te [2-5] which should be clarified soon [6]. I will be concerned here only with future direct experiments aiming to discover the lepton violating neutrinoless channels. Some of them consist in the enlargement of setups similar to those presently used, while others are based on new detection techniques. All can be divided into two groups: the *source≠detector* experiments where the material containing the DBD candidate is inserted in a suitable detector, and the *source=detector* one [7] where detector is made of a DBD active material,

An easy parameter to evaluate "a priori" the sensitivity of a DBD experiment is the limit reachable on the lifetime, which we could roughly be defined as:

$$T_{1/2} \sim 4.2 \times 10^{26} \frac{\text{i.a.} \times M^{1/2} \times t^{1/2}}{A \times B^{1/2} \times \Delta^{1/2}} \times \varepsilon \text{ years} \qquad (1)$$

Where A is the atomic weight, i.a., the isotopic abundance, M the mass in kg, t the time of measurement (in years) , B background counting rate in the region of neutrinoless DBD (in counts keV^{-1} y^{-1} kg^{-1}) , Δ the energy resolution in keV and ε the efficiency. The strategy of a future DBD experiment is summarized in Table I.

What is relevant in searches on neutrinoless DBD is the extracted limit on the average neutrino mass $<m_\nu>$ which depends not only on T, but also on phase space (roughly proportional to the fifth power of the transition energy) and on the value of the nuclear matrix element.

3. DBD EXPERIMENTS BASED ON CONVENTIONAL TECHNIQUES

NEMO 3

This experiment [8] is already in construction and will operate at the beginning of the next year in the Frejus underground laboratory at a depth of ~ 4800 meters of water equivalent (mw.e.). The scheme of this source≠detector setup is shown in Fig.1. It consists in a tracking system made by drift wire chambers operating in Geiger mode filled with a gas mixture of Helium and ethyl alcohol. It is completed by a calorimeter made by 1949 plastic scintillators. The entire setup is kept in a magnetic field of 30 gauss. Typical of this experiment is the possibility of inserting different DBD active sources. Considerable amounts of enriched materials are in fact available to this collaboration and searches for DBD of ^{100}Mo , ^{82}Se ,^{116} Cd and later of ^{113}Te, ^{150}Nd, ^{96}Zr and ^{48}Ca are planned. Due to the excellent command of the background and intrinsic radioactive contamination of the source element, but the relatively modest resolution the limit in the sensitivity on neutrinoless DBD could come from the "background" on two neutrino DBD events! Sensitivity on $<m_\nu>$ better than 0.1 eV are however expected.

GENIUS AND MAJORANA

Two experiments on DBD ^{76}Ge based on very large arrays of enriched germanium diodes have been proposed.

The **G**ermanium in liquid **N**itrogen **UN**derground **S**etup proposed by a Heidelberg - Moscow collaboration (Fig.2) would consist in an array of 400 large Ge diodes enriched in ^{76}Ge with a total mass around a ton [9]. They will be shielded by a very large tank of liquid nitrogen where these *naked* germanium diodes would be operating. The proposers hope that liquid nitrogen will be purified at a very high level, like for instance the liquid scintillator in BOREXINO. On the other side adoption of a low Z shield will necessarily imply a very large detector, with some difficulty for its underground installation. Careful measurements have been performed with three naked Ge detectors of ~300 grams which have been operated successfully in a 50 liter dewar in the Gran Sasso Underground Laboratory. An energy resolution of ~ 1 keV @ 300 keV and a low energy threshold of ~ 2.5 keV have been reached.

Due to the cost and time required to enrich such a large mass of Germanium this collaboration have presented a test experiment named GENINO (the real name should in fact be GENIETTO!), presently being considered by the Scientific Committee of the Gran Sasso Underground Laboratory. This setup, devoted to searches on direct interactions of WIMPS, will consists of 100 kg on natural Ge detectors + 2 kg of ^{73}Ge diodes in a 5 m diameter liquid nitrogen tank, with an additional shield of 20-30 cm of lead or 50 cm of Iron. It will also allow direct prediction on the final sensitivity of GENIUS. Present detailed Monte Carlo calculations by the Heidelberg group indicate a final sensitivity of GENIUS better than 0.01 eV on the average neutrino mass.

The **MAJORANA** project [10] has been proposed more recently by American groups (Duke, Pacific Northwest National Laboratory, New Mexico, Argonne) together with Dubna and Kurchatov and ITEP in Russia. This collaboration, which have already started the GUERNICA experiment on DBD to excited nuclear levels, plan to install 500 kg of ^{76}Ge enriched diodes in a new underground laboratory operated by DOE in New Mexico.

MOON

An experiment [11] to study both double beta decay and solar neutrinos [12] has been recently proposed by groups of the Universities of Washington, North Carolina and Wisconsin and the RCNP of Osaka. As shown in Fig. 3 the DBD active nucleus ^{100}Mo is also an excellent target for solar neutrinos, with a threshold of 0.186 MeV only. The detector would consist of foils of natural molybdenum interleaved with plastic scintillator modules. The setup will have a fiducial volume of 6x6x5 m and will consists of 1950 modules of 6m x 6m x 0.25 cm with a total mass of 40 tons of natural molybdenum, corresponding to 3.3 tons of ^{100}Mo. The expected sensitivity on the average neutrino mass is of ~ 0.03 eV.

DCBA

The aim of this proposed **D**rift **C**hamber **B**eta **A**nalyzer [13] is the measurement of the momentum of each electron in DBD and the position of the decay vertex with the three dimensional reconstruction of the entire event in an uniform magnetic field. The standard module of this setup consists of a drift chamber of 46.4 x 52.4 x 68.0 cm^3 inside a solenoidal coil and a cosmic ray veto. The detector is expected to measure the energy of each electron with a FWHM resolution of 140 keV and to determine also their angular correlation, with a strong reduction of the background. The DBD active source can be easily changeable, the preferred nucleus being presently ^{150} Nd.

CAMEO

This proposed experiment follows a previous proposal [14] for a search on DBD of ^{136}Xe by dissolving this gas in the liquid scintillator of BOREXINO and/or of the Borexino Counting Test Facility .(CTF) .This new proposal [15] by the Kiev and Milano groups, foresee as a first step the insertion in CTF of three mutually orthogonal disks of about 1 kg of a DBD active nucleus (^{100}Mo, ^{116}Cd, ^{82}Se, ^{150}Nd). A second step would consist in the installation in CTF of crystals of $CdWO_4$ enriched in ^{116}Cd .

4. DBD EXPERIMENTS BASED ON NEW TECHNIQUES

The peculiar requests of DBD experiments as well as the generally felt need to investigate different nuclei has stimulated the use of new, recently developed, techniques.

The employment of thermal detectors for DBD experiments has been proposed since 1984 [16]. The principle consist in the operation of a diamagnetic and dielectric crystal where the heat capacity at low temperature is dominated by the Debye law:

$$C_V = 1944 \frac{V}{V_m} \text{ x } \left(\frac{T}{\Theta}\right)^3 \text{ Joule/ Kelvin} \qquad (2)$$

Where V and V_m are the detector and molar volumes, and T and Θ are the operating and Debye temperatures, respectively. These bolometers [17-19] could in principle achieve energy resolution quite superior than those of any other detectors (~.1 eV and 10 eV, for masses ranging from milligrams to kilograms, respectively). In practice microbolometers have reached resolutions of ~ 5 eV for 6 keV X-rays [20]. Large detectors of the order of a chilogram, as those needed for DBD experiments, yield already the same resolution as Ge diodes for high energy γ rays and a resolution superior to that of any other detector for α particles [21]. A promising feature of these bolometers in DBD source=detector experiments is the ample choice of DBD candidate nuclei. Many candidates for searches in DBD are reported in TableII, where thermal (large Debye temperature) and mechanical properties are taken into account.

Crystals made with all these compounds have been operated at low temperature by our group. In particular a crystal of natural calcium fluoride have been operated as a "scintillating bolometer" by recording simultaneously both heat and scintillation pulses [22]. This would in principle allow selecting by coincidence double beta decay of ^{48}Ca by eliminating the background of the poorly scintillating α particles. The same should be true also for ^{100}MoPbO$_4$ and ^{116}CdWO$_4$. We have successfully operated bolometers with both these materials, but so far only in the thermal mode. An excessive counting rate was however found in the former one, due to the presence of the radioactive contamination of ^{210}Pb. Roman lead should be used! Efforts have been also devoted to operate crystals of NdF$_2$: they were however found to be difficult to cool below 70 mK. Crystals of Germanium have been operated thermally with a resolution similar to Ge diodes. A thermal experiment with a large array of Ge crystals could be therefore competitive with those with Ge diodes, also because there would be no requirement on the absence of electronegative impurities.

The only "thermal' experiment carried out so far is being performed [1,6] with 20 crystals of natural TeO$_2$, taking advantage of the good transition energy and large natural abundance of ^{130}Te. The Berkeley, Florence, Gran Sasso, Neuchatel, South Carolina and Zaragoza groups have proposed a very large experiment with this compound.

CUORE

This Cryogenic Underground Observatory for Rare Events [23] would consist in principle of 1020 cubic crystals of 5 cm side of natural TeO$_2$, corresponding to a total active mass of 775 kg , or 210 kg of ^{130}Te. It can already be installed in the Gran Sasso Undergroud Laboratory and would be devoted to the study of DBD, interactions of WIMPS and solar axions , and more generally to search for rare low energy nuclear events. The limit on the average neutrino mass extrapolated on the background of the present 20 crystal array is of 0.1 eV , but could be considerably improved if this background will be substantially reduced. This will be probably accomplished by eliminating surface contamination (a typical background source in thermal detectors) and by applying anti-coincidences with nearby detector. One should in fact note that in arrays of bolometers there is no material between them , unlike in arrays of Ge diodes.

A preliminary experiment, named **CUORICINO**, made by 56 crystals of the same mass as CUORE, has been approved and funded and is being mounted in the Gran Sasso Underground Laboratory (Fig. 4). Arrays of four crystals of this size have been already operated reaching an energy resolution similar to that of Ge diodes for high energy γ rays and better than with any other detector for α particles.

EXO

This Enriched **X**enon $\beta\beta$ decay **O**bservatory is being proposed by a collaboration among groups in Italy, Russia, Switzerland and USA [24] and is based on a totally new technique. The setup would consists in a Xenon Time Projection Chamber with background suppression by tagging with laser the Ba ions produced by DBD . The scheme of this experiment is shown in Fig. 5 . ^{136}Xe double beta decays into ^{136}Ba^{++} which are then reduced by quenching to singly charged ^{136}Ba^{+} ions. This ions remain for a reasonable time in the same region of a Xenon TPC at 5 atmosphere (they diffuse of 0.7 mm only in one second). During this period they can therefore be cyclically excited 10^7 times by a double laser pulse. The initial $6^2S_{1/2}$ state is excited by a first 493 nm laser pulse to the $6^2P_{1/2}$ which then decays with a 30% branching ratio to the metastable $5^4D_{3/2}$ state. This can be excited by a second 650 nm laser beam to $6^2P_{1/2}$ which return to the initial $6^2S_{1/2}$ with the emission of a 493 nm photon.

The present plan is for the construction of a 40 m^3 Xenon TPC kept at 5-10 atm containing the therefore 1-2 tons of ^{136}Xe with the goal to reach a sensitivity from 0.02 to 0.04 eV on the average neutrino mass.

CONCLUSIONS

The future of double beta decay shows a flourishing of theoretical and especially experimental activities. The two neutrino DBD process still maintains considerable interest, also in view of solving problems which still remains in geochemical searches and of testing theoretical predictions. There is no doubt however that the main interest is presently addressed to the existence or not of neutrinoless double beta decay as a powerful tool to test the lepton number conservation and to set indirectly a limit on the average neutrino mass. Even if great progress has been done in theoretical calculation, further effort would be welcome, especially on theories based on results on devoted experiments on the intermediate nucleus which could strengthen the reliability of the calculation of nuclear matrix elements.

Planned experiments based on conventional techniques have already reached impressive reduction of the background, comparable only to those attained in solar neutrino and dark matter experiments. Improved methods like e.g. pulse shape discrimination can still improve the present results. Larger masses of the candidate nuclei are obviously desirable . With a few exception of nuclei with a large natural abundance (e.g. ^{130}Te) a substantial increase of these mass requires expensive isotope enrichment which are at present , in the words of David Caldwell, a "fiscal impossibility". New methods, especially for nuclei which cannot presently be enriched by centrifugation, could radically change the future of double beta decay.

Considerable interest should be devoted to the development of new techniques which could overcome many difficulties of the present experiments and extend searches of DBD to a larger choice of candidate nuclei (also for the two positron, positron plus EC and 2 EC channels). Searches for DBD could be quite useful also for other experiments on rare decays as it has been the case in the past (remember that the first experiments on direct detection of WIMPS have been carried out, on suggestion by Frank Avignone, with DBD setups!).

Not only evidence, but also not even hints, has been presented so far for the dreamed peak in the electron sum energy corresponding to neutrinoless double beta decay. Let us hope however, as hoped many years ago by Peter Rosen, that the brilliant discovery of two neutrino DBD in many nuclei will be the "Cuckoo Song in the Spring" and will anticipate the glorious summer of the discovery of the neutrinoless channel.

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FIGURE CAPTIONS

Fig. 1 : Scheme of the NEMO 3 experiment

Fig. 2 : Scheme of the GENIUS experiment

Fig. 3 : Nuclear scheme for DBD and neutrino interactions in ^{100}Mo

Fig. 4 : Scheme of CUORE and CUORICINO (essentially one column of CUORE)

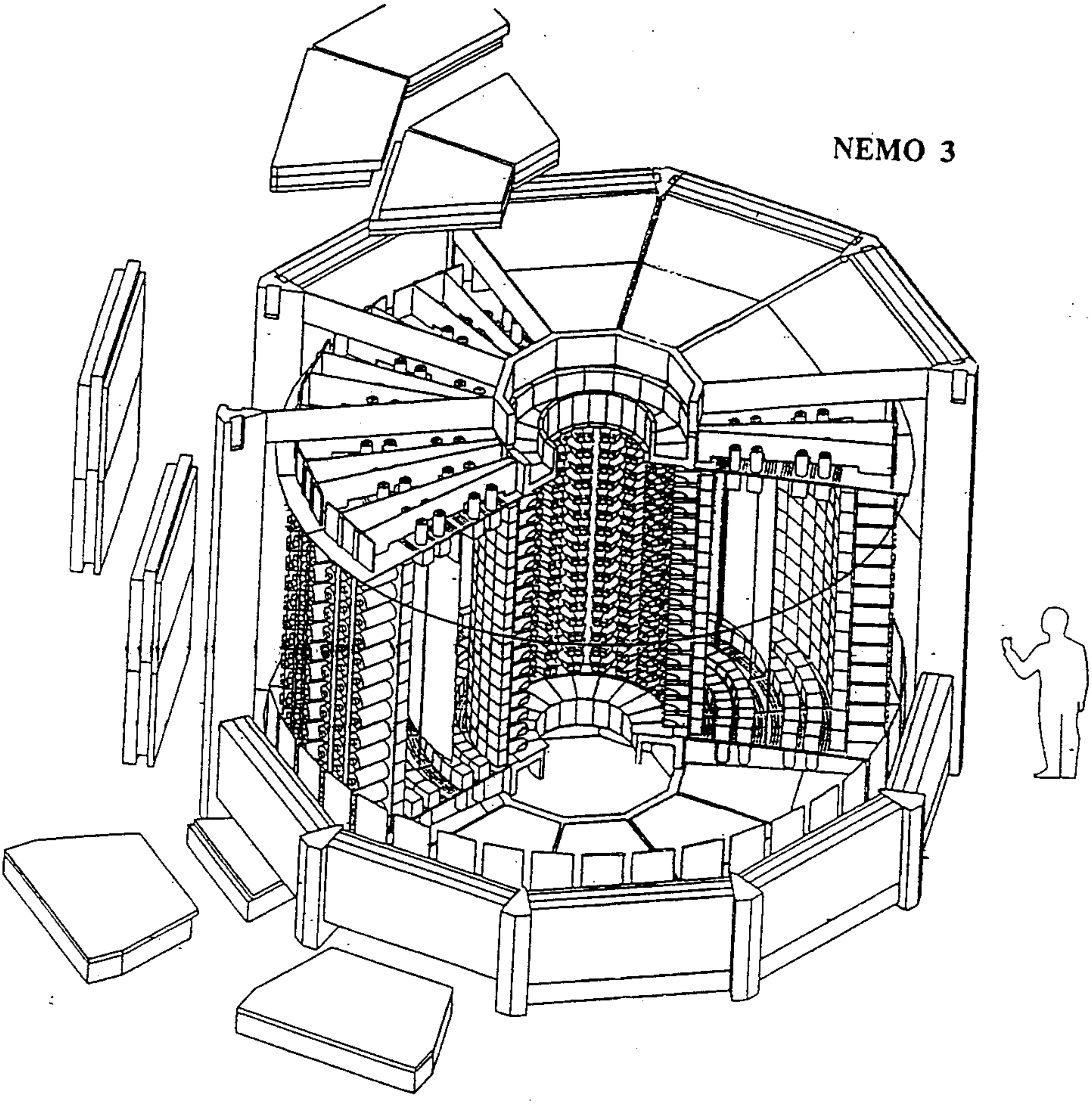
Fig. 5 : The atomic scheme for cyclic excitation of Ba$^+$ and the EXO setup.

Table I

How to improve the sensitivity of a neutrinoless DBD experiment	
Improve isotopic abundance	Expensive and could worsen the background
Increase the mass	Expensive and technically difficult
Run for a longer time	Tedious
Reduce the background	Already at a level of less then 0.1 counts keV^{-1} y^{-1} kg^{-1}
Improve the energy resolution	Germanium and thermal detectors are already reaching a ΔE/E level of less than a part per thousand
Efficiency	Near 100% in source=detector experiments
Nuclear matrix elements	**Could vary considerably, and should be studied** carefully. Decay to excited O^{+*} states could be favored. Different candidate nuclei should be tested

TABLE II: Compounds for thermal searches on neutrrinoless DBD

Compound	Isotopic abundance of DBD candidate	Transition energy (keV)	Comment
$^{48}CaF_2$	0.187 %	4272	Good thermal detector and scintillator. Difficult to enrich
^{76}Ge	7.44 %	2038.7	Good thermal detector
$^{100}MoPb\ O_4$	7.49%	2804	Thermal detector and scintillator. ^{210}Pb contamination
$^{116}CdPbO_4$	9.63	3034	Good thermal detector and scintillator.
$^{130}TeO_2$	34	2528	Good thermal detector
$^{150}NdF_2$	4.64	3368	Difficult to cool.Could scintillate


NEMO 3

Design of the GENIUS facility

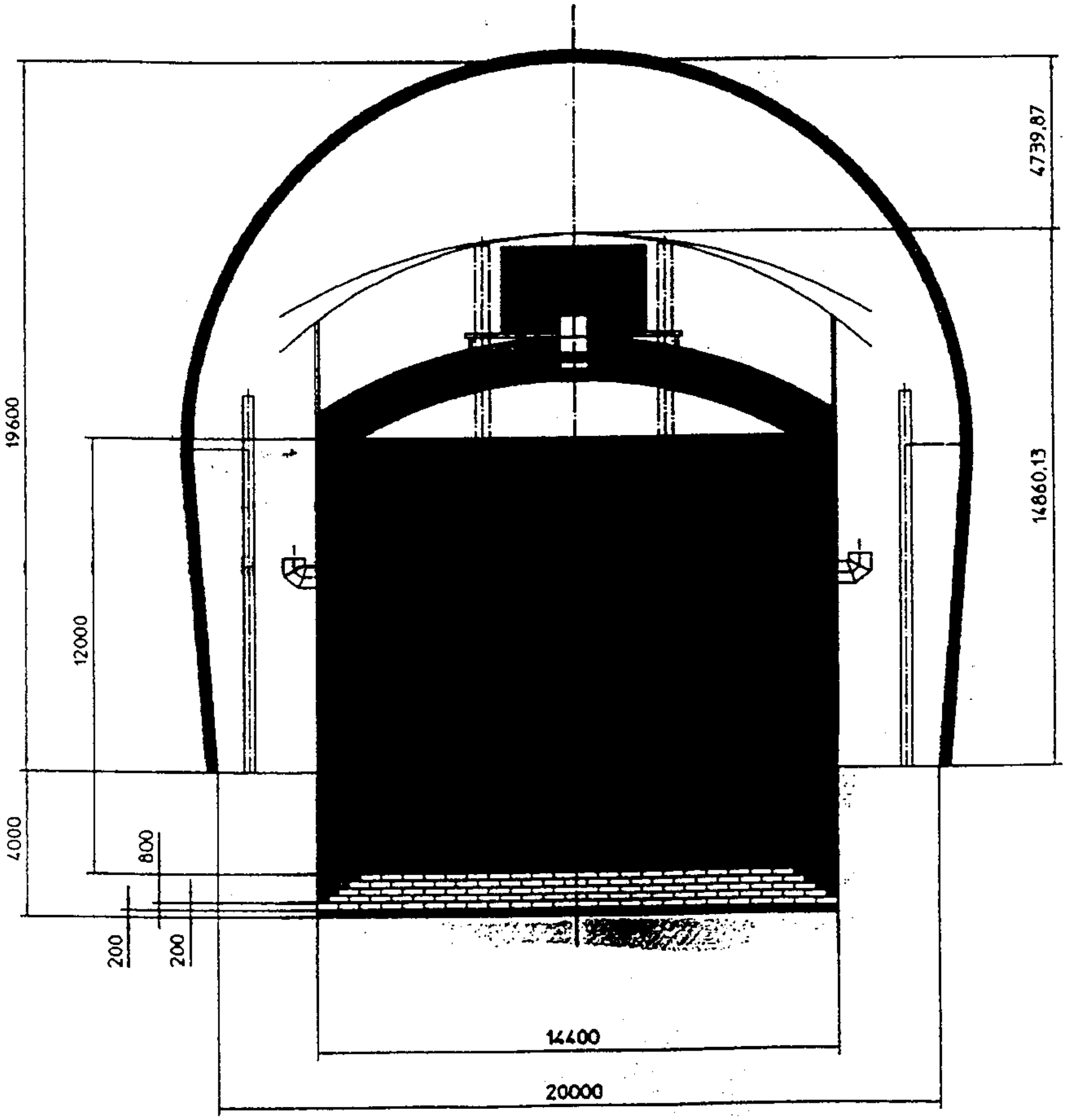
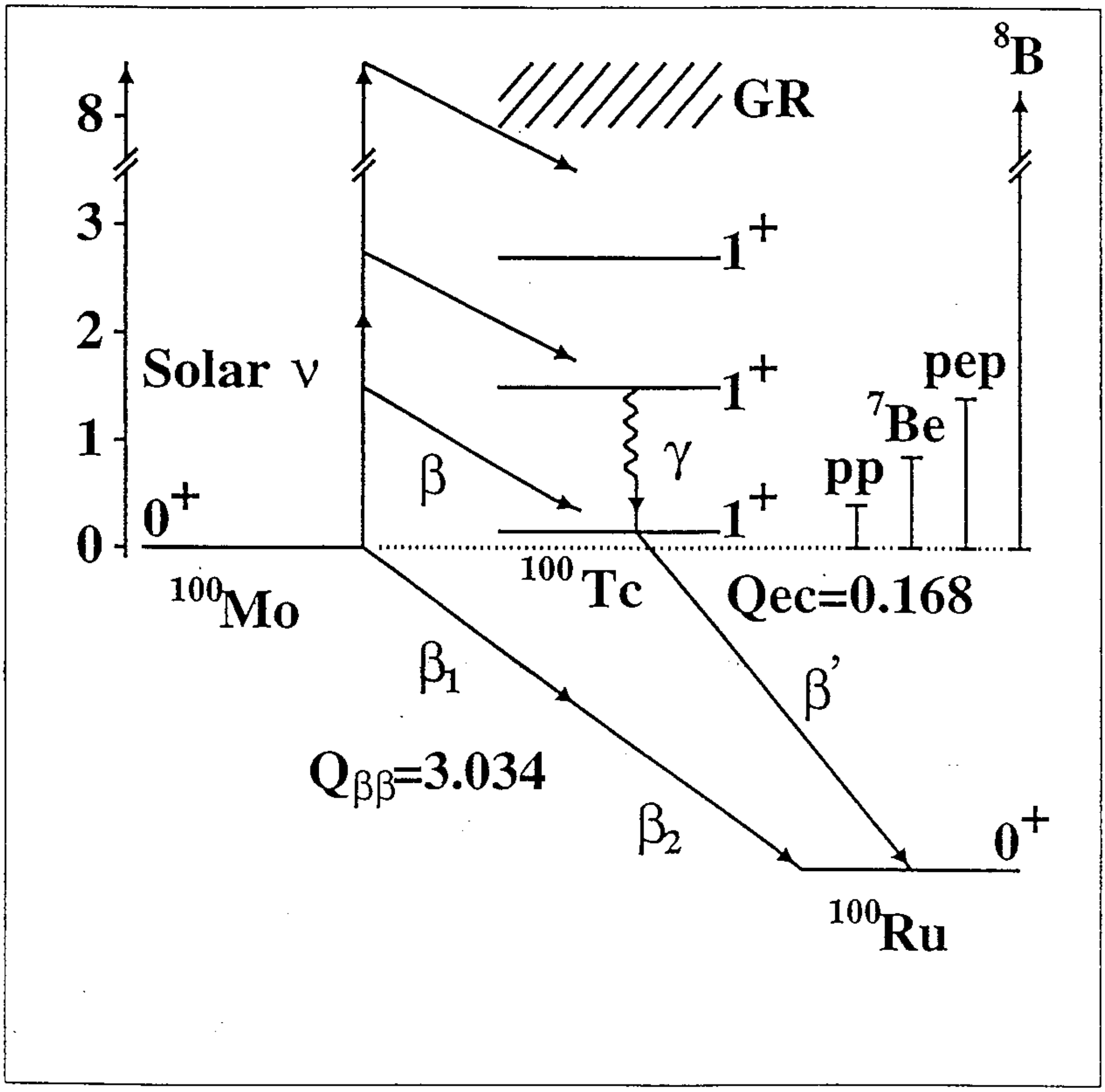


Fig.2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3
2
1
0
GR
1^+
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Solar ν
β
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β_2
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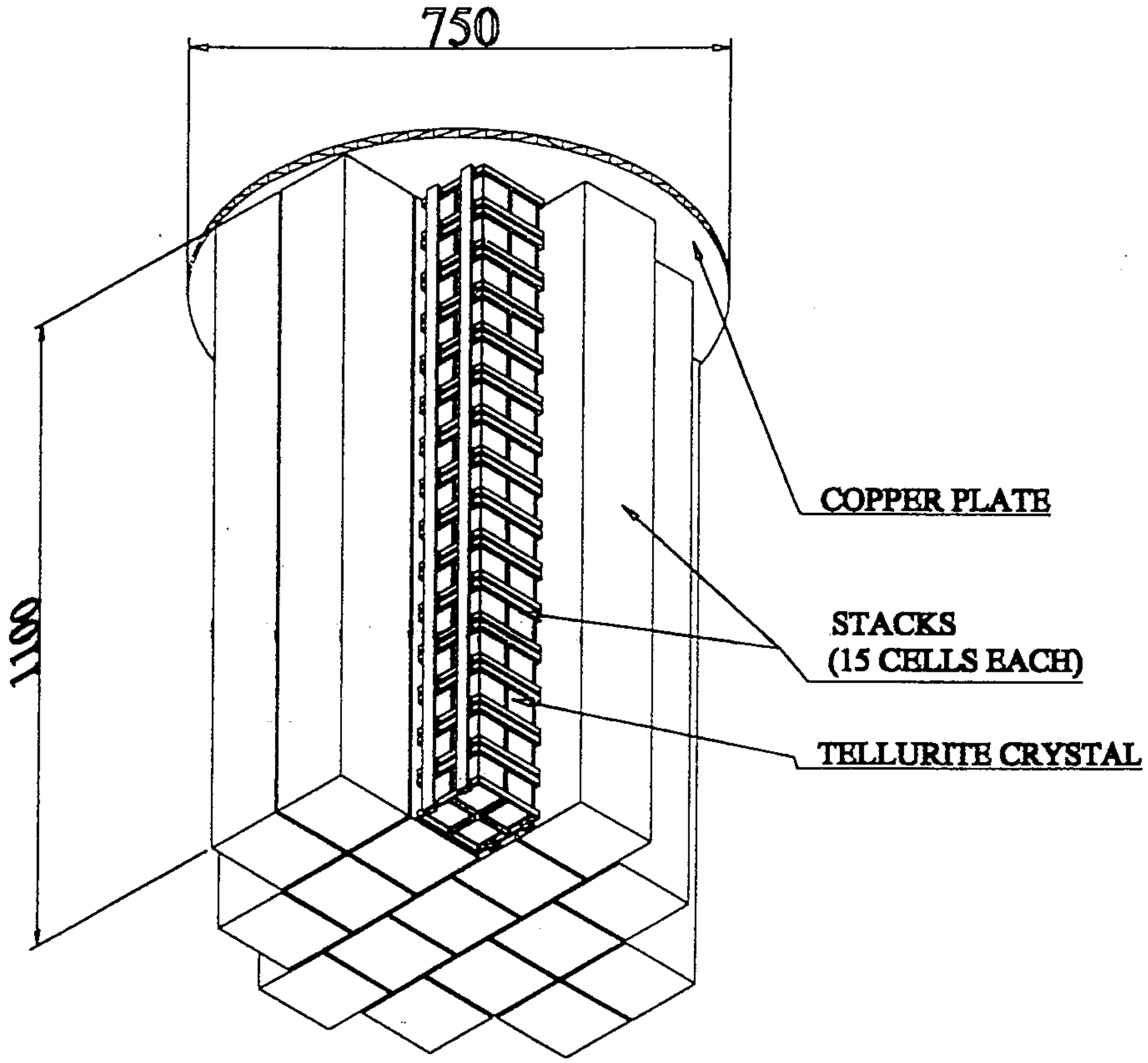
Fig 3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1100
COPPER PLATE
STACKS
(15 CELLS EACH)
TELLURITE CRYSTAL

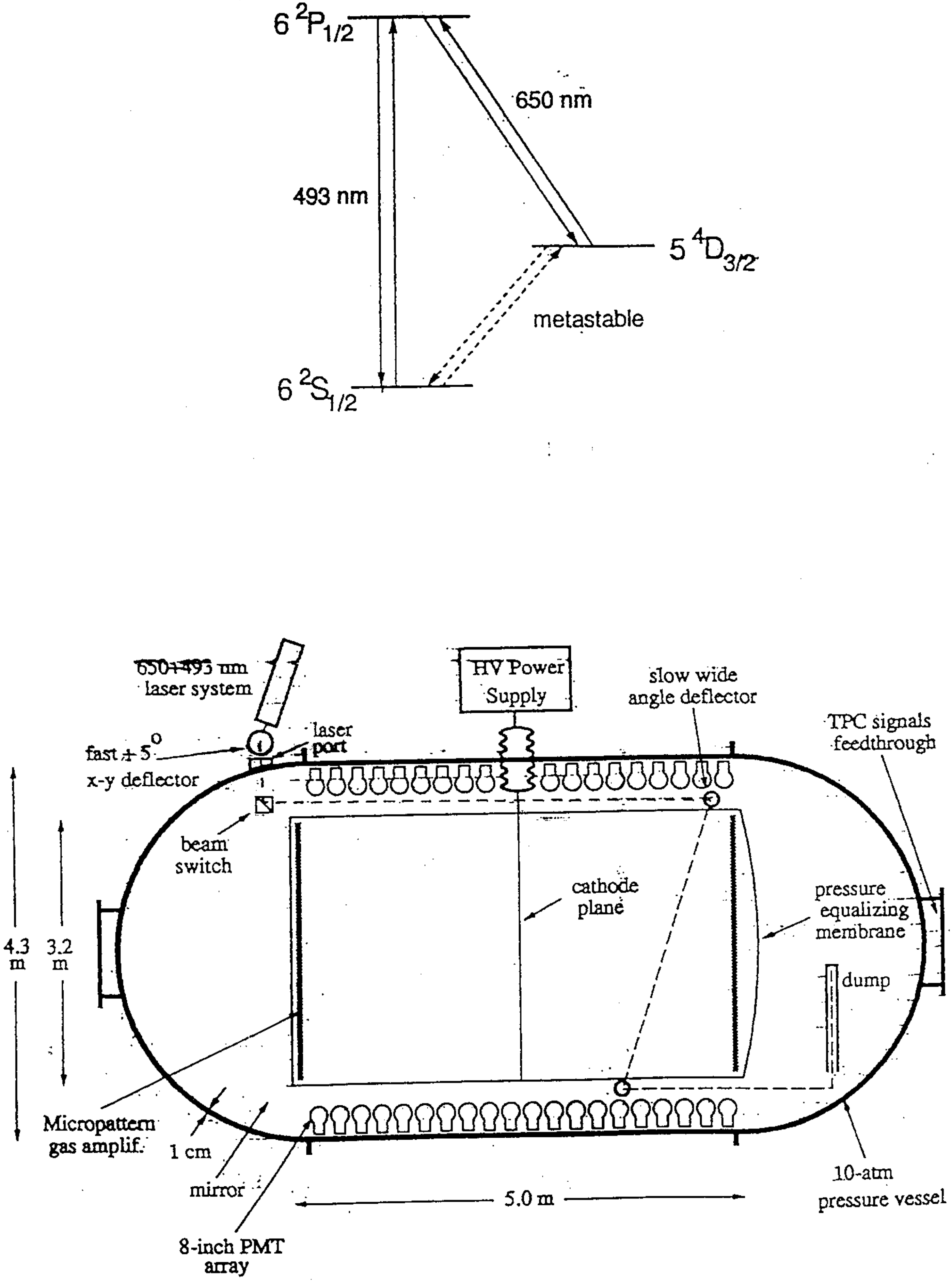
$6\,^2P_{1/2}$
650 nm
493 nm
$5\,^4D_{3/2}$
metastable
$6\,^2S_{1/2}$
650+493 nm
laser system
HV Power
Supply
slow wide
angle deflector
TPC signals
feedthrough
fast ± 5°
x-y deflector
laser
port
beam
switch
cathode
plane
pressure
equalizing
membrane
dump
4.3
m
3.2
m
Micropattern
gas amplif.
1 cm
mirror
5.0 m
8-inch PMT
array
10-atm
pressure vessel

Fig.5