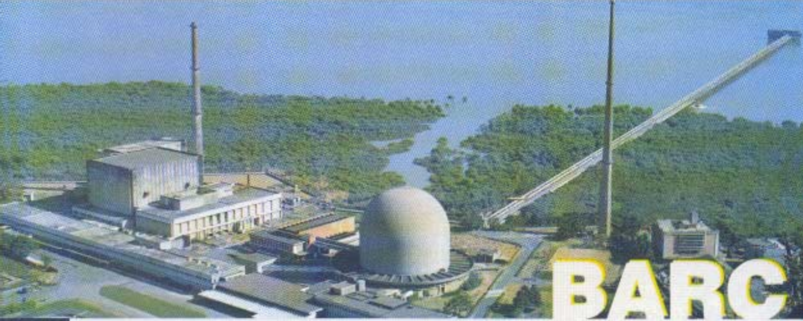

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Contents

1. Development of neutron well coincidence counters for the non - destructive assay of plutonium at various stages of nuclear fuel cycle 1
2. Quantum information, computation and fundamental limitation 7
3. Scientists visit aquaculture farms and fish processing units 14
4. National symposium on environment 15
5. BARC scientists honoured 16

DEVELOPMENT OF NEUTRON WELL COINCIDENCE COUNTERS FOR THE NON-DESTRUCTIVE ASSAY OF PLUTONIUM AT VARIOUS STAGES OF NUCLEAR FUEL CYCLE

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Non-destructive assay techniques (NDA) based on neutron measurements play an important role in the assay of plutonium in various stages of the nuclear fuel cycle. The NDA techniques find wide ranging applications in quality control of finished products, nuclear material accounting, process control and safeguards. The non-destructive assay techniques are direct, fast and amenable to automation. These techniques are versatile with respect to chemical composition and physical configurations, unlike the conventional chemical techniques which are more accurate but slow and need more rigorous sampling. The non-destructive assay techniques can be classified as passive or active depending on how the response is obtained. In the passive mode, the radiations from the natural radioactive decay of the isotopes of interest are monitored. In the active mode, the delayed neutrons/prompt neutrons or gamma rays from the samples irradiated by the neutrons are monitored. The passive mode based on neutron counting is best suited for heterogeneous samples of various configurations compared to passive gamma counting because of the associated problems of self attenuation and low abundance of gamma rays. In Radiochemistry Division, extensive work has been carried out for the development of Neutron Well Coincidence Counters (NWCC). Following is an overview of the development work, wide ranging applications at Fuel Fabrication Facilities, reprocessing plants and Radiochemical Laboratories.

Origin of Neutrons in Plutonium Samples

The neutrons emitted by a plutonium-bearing sample consist of spontaneous fission (SF) neutrons from even-even plutonium isotopes ($^{238,240,242}Pu$) as well as (α, n) neutrons induced by interaction of alpha particles with low Z elements like, O, C, F, Al etc.

Neutron Detectors

Neutrons are detected through nuclear reactions which may result in energetic charged particles, capture gamma rays, fast recoils, conversion electrons or fission products. The thermal neutron reactions with ^3He, ^{10}B and ^6Li result in charged particles which can be detected by ionisation or scintillations in a suitable medium. Most of the neutron sources also emit gamma rays and it is required to discriminate against gamma response of the neutron counters. The gas filled counters based on ^3He and ^{10}B and fissile materials offer more effective gamma discrimination. The Q value of the reaction is also important which determines the energy liberated in the reaction. The higher the Q value, the greater is the energy liberated and it is possible to discriminate against the gamma rays by simple pulse height discrimination. ^3He detectors have higher efficiency because of high neutron absorption cross section for thermal neutrons and higher possible fill pressures up to 4 atm. Comparatively, BF_3 detectors are less efficient because pulse degradation limits fill pressures and lowers thermal neutron absorption cross section and natural abundance of ^{10}B, though the Q value for neutron reaction with ^3He (0.760 MeV) is lower than that of ^{10}B (2.310 MeV). For neutron measurement of highly gamma active samples, BF_3 detectors are preferred as better gamma discrimination is possible. For the passive neutron assay of plutonium, ^3He counters are used because of availability of high efficiency compact detectors. The neutron absorption cross section decreases rapidly as the neutron energy increases and hence moderation of neutrons is necessary to increase the detection efficiency of the counting system. The neutron detectors are required to be housed in a suitable moderator assembly for enhancing the detection efficiency of the counting system.

Moderator Assembly and Counter Configuration

The important characteristics of a good moderator are high moderating ratio, ease of fabrication and low cost. In early development, paraffin was used for the fabrication of moderator assemblies for neutron counters. Presently, High Density Polyethylene (HDPE) sheets are available and moderator assembly is fabricated using this material. Thermal neutron absorption cross section of hydrogen is significant (0.33 b) and hence a thickness of HDPE sheet of about 3 cm is optimum for moderation. A thickness of about 6 cm can be used as reflector to enhance the detection efficiency. The design of neutron well counter provides the highest possible counting efficiency and the best configuration for biological shielding. The sample to be assayed is placed in the central well of the counter. An important feature of the well counter is also the reasonably good flat response over the volume of the well, which is important for heterogeneous samples. Typically 6-24 counters are arranged in a circular array around the central well [2].

A schematic of the associated electronics of the neutron counting setup is given in Fig. 1.

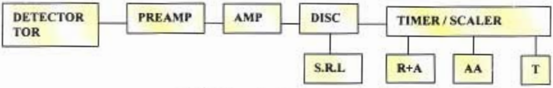

Fig. 1. A schematic of the neutron counting system

Total Neutron Counting

Gross neutron counting is adequate for isotopically well characterised plutonium in homogeneous and well defined chemical matrix. For higher amounts of plutonium, multiplication effects come into play because of the fissions induced by source neutrons in fissile plutonium isotopes ($^{239,241}Pu$). The SF neutrons are mainly from $^{238,240,242}Pu$ isotopes and effective $^{240}Pu_{eff}$ mass is defined as

$$^{240}Pu_{eff} = 2.43\ M_8 + M_0 + 1.69\ M_2 \qquad (1)$$

where, M_8 , M_0 , M_2 are the weight percentages of the isotopes, ^{238}Pu , ^{240}Pu and ^{242}Pu respectively. The constants 2.43 and 1.69 account for specific spontaneous fission neutron production in ^{238}Pu and ^{242}Pu relative to ^{240}Pu.The (α, n) yields per g/s are calculated from the knowledge of isotopic and chemical composition of plutonium in the sample. The absolute detection efficiency of the counter is determined using the standard ^{252}Cf neutron source. The total neutron counting is carried out routinely for the assay of plutonium in low level nuclear waste packets for taking a decision on disposal or recovery. However, in the case of heterogeneous samples having unknown chemical composition, the (α, n) yields cannot be accurately estimated and coincidence counting of neutrons has to be used for the estimation of plutonium.

Coincidence Counting of Neutrons

Fission events yield multiple neutrons that are correlated in time, whereas (α,n) reactions and background events yield single neutrons that are uncorrelated or random in time. Coincidence counting of time correlated fission neutrons is a powerful technique for distinguishing the fission neutrons from (α, n) and background neutrons. The Rossi Alpha distribution [2] obtained from the distribution of arrival times of the neutron pulses from a detector is the basis for obtaining the random (A) and real coincidences (R). This is the distribution in time of events that follow after an arbitrarily chosen starting event. If only random events are being detected, the distribution is constant with time. If real coincidences are also present, the distribution is given by

$$S(t) = A + R \exp(-t/\tau) \qquad (2)$$

where τ is the mean life time of the neutron in the counter, called or die away time of the system. Die away time depends upon size, shape, composition of the counting system. Typical values are in the range of 30 – 100 μs for neutron Well Coincidence Counters. Therefore, the conventional coincidence circuits require large dead time corrections. An alternative approach is the Shift Register Logic [3, 4, 5] which eliminates the dead time effect and allows operation at higher count rates. The sum of real and accidental (R+A), only accidental (A) and total (T) are obtained by the shift register based coincidence logic. The difference of (R+A) and (A) gives the real coincidences (R) and is proportional to the effective ^{240}Pu mass.

Multiplication Correction

For samples containing larger than few tens of grams of plutonium, the SF and (α,n) neutrons may induce fissions in $^{239,241}Pu$. The neutron induced fissions may also be caused by slow neutrons reentering the sample placed inside the neutron well counter. These fissions are having higher neutron multiplicity than the SF events. Hence they contribute to the enhancement of coincidence response and introduce non linearity in the response for higher amounts. The standard methods have been developed for multiplication corrections [5]

Development of a Neutron Well Coincidence Counters in Radio-chemistry Division

The development was started in early 1990 and the first High Level Neutron Well Coincidence Counter (HLNCC) was developed in 1985 [1]. Shift Register based coincidence logic units were fabricated and tested for the first time. Components were designed and fabricated for the parallel connection of multiple ^{3}He counters to ensure safe application of detector bias and proper grounding to minimise noise and pickup contributions. The linearity of the coincidence response of the HLNCC using CIRUS grade PuO_2 standards (100-1200g) is shown in Fig. 2.

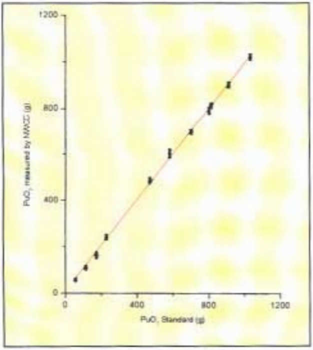

Fig. 2 Linearity of coincidence response for HLNCC

A large number of PuO_2 lots, waste packets, (U,Pu)C samples, plutonium bearing graphite crucibles from Radiometallurgy Division, BARC were assayed for plutonium. Assay of plutonium in fuel materials and waste packets in Radiochemistry Division and Fuel Chemistry Division laboratories is being carried out routinely. Assay of ^{233}U in fuel plates of KAMINI reactor was carried out for the quality control during the fabrication at RMD, BARC. A similar unit was fabricated for Fuel Reprocessing Division, BARC and is being used routinely for the assay of PuO_2 lots. The know how developed was useful in setting up similar units at Advanced Fuel Fabrication Facility (AFFF), Tarapur and FCD, IGCAR In A3F, NWCC is being extensively used for the determination of plutonium in MOX blends to ascertain Pu enrichment at the powder mixing stage [6]. It is also proposed in A3F to qualify the sintered pellets by NWCC instead of chemical analysis. The proposal is intended to reduce liquid waste generation, process time as well as man power requirement. The method is also used for rapid identification of PHWR and Research Reactor grade plutonium oxide lots [6].

A mobile neutron slab coincidence counter was also developed for in-situ assay of large amounts of plutonium in sealed containers which cannot be brought to the neutron counting station. The unit has been calibrated for coincidence and gross neutron efficiency and is being used in Radiometallurgy Division.

Assay of Plutonium in FBTR Sub Assemblies

A new type of Neutron Well Coincidence Counter was developed [7] for non-destructive assay of plutonium in FBTR fuel pins and sub assemblies. The plutonium in the pins is of PHWR grade (^{240}Pu in the range of 18–24%) and the amount of plutonium in a sub assembly is about 1.6 kg. The total neutron emission rate of the subassembly consisting of spontaneous and (α,n) neutrons is about 10^5 n/s. The precision of coincidence counting of fission neutrons is affected by the presence of (α,n) neutrons in the sample. Also the large amount of plutonium in the sample leads to multiplication effects giving rise to nonlinear response. So it is necessary to take into account the multiplication and minimise the effect of (α,n) neutrons in coincidence counting. The active length of the fuel pin is 320 mm and the axial response of the counter should be flat over the active region. Incorporating these considerations, a HDPE moderated, ^{3}He detector based system has been designed and fabricated for the non-destructive assay of plutonium in FBTR fuel sub assembly. Reduction of ambient background, multiplication effects and the die away time were achieved by suitable positioning of cadmium sheets of 0.4 mm thick in the moderator assembly. The die away time is reduced to enhance the real coincidences relative to the random coincidences. Six ^{3}He neutron detectors (50 cm sensitive length, 2.54 cm dia , fill pressure 4 atm.)

are arranged symmetrically in a circular array around a well of 120 mm. dia. for positioning the fuel pins. In order to facilitate smooth handling of a large number of pins for the assay purpose, a FBTR fuel pin holder was specially designed and fabricated in collaboration with RMD and Central Workshops, BARC. The fuel pin holder (fig.3) can hold a total of 61 pins in hexagonal lattice. A total of 61 pins containing plutonium of similar isotopic composition were made available in RMD for carrying out the measurements. Extensive experimental data was obtained using different combinations of available pins. The linearity of total and coincidence response as a function of $^{240}Pu_{eff.}$ (fig.4), which corresponds to plutonium amounts in the region of 27g – 1600g. was established.

Fig. 3 Assay of plutonium in FBTR fuel pins

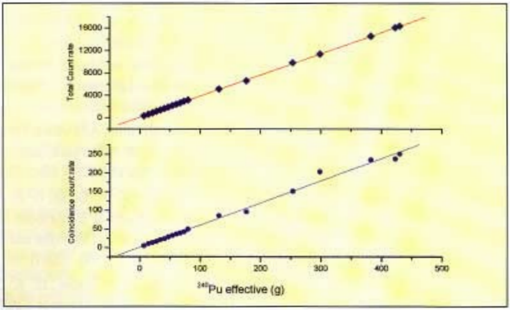

Fig. 4 Variation of coincidence and total count rates as a function of effective ^{240}Pu mass for FBTR fuel pins.

Recent Development in Data Acquisition System for Neutron Counting

A PC based data acquisition system is recently developed for sequential recording of the arrival times of the pulses from a neutron well counter [8]. The system consists of a Personal computer (PIII 700 MHz and 128 MB RAM) with PC compatible card PCL-830 which is a multifunction counter/timer and digital I/O card. Two Advanced Micro Devices (AMD9513) system timing and controller chips are used for all counting and timing functions. The hardware configuration of the system is given in fig 5. Methodology was developed for the analysis of the data to obtain the real time correlated events as well as the die away time of the system.

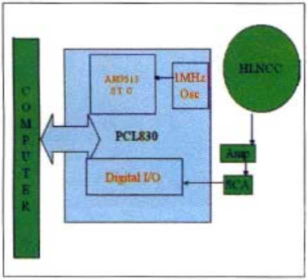

Fig. 5 Hardware configuration of PC based data acquisition system

Standard ^{252}Cf neutron sources were used to test the linearity of the response of real time correlated neutrons and PuF_4 (α, n) source was used to obtain the random neutron response (Fig.6). The new data acquisition system is more versatile alternative to the conventional shift register based neutron coincidence counting system.

In conclusion, the development of the non-destructive assay techniques is need based and has to be carried out to meet the specific requirements of the users.

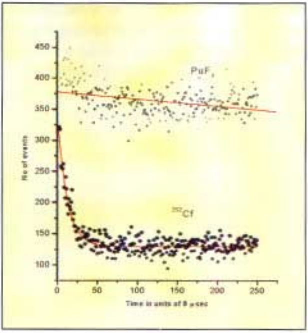

Fig. 6 Rossi Alpha Curve for PuF_4 and ^{252}Cf sources

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QUANTUM INFORMATION, COMPUTATION AND FUNDAMENTAL LIMITATION

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Introduction

Quantum information theory is a marriage between two scientific pillars of the twentieth century science, namely, quantum theory and classical information theory. Quantum theory as developed by Planck, Einstein, Schrodinger, Dirac, Heisenberg, and many others in early part of the last century is one of the finest theories that explains phenomena ranging from molecules to electrons, protons, neutrons and other micro particles. Mathematical theory of classical information was also propounded by C. Shannon in the midpart of the last century. Whatever revolution in information technology we see at present is partly due to the ground-breaking work by C. Shannon, A. Turing, A. Church and many others.

When the ideas from classical information theory are carried over to quantum theory there emerges a revolution in our ability to process information. The very basic ways of expressing and manipulating information require physical states and processes. In quantum theory we know that the physical processes are fundamentally different than those of classical physics. Therefore manipulation of information based on quantum physical processes has to be also fundamentally different than their classical counterparts [R. Feynman, *Found. of Physics* **16** (1986) 507]. It is this urge to understand what we can do with the new ways of expressing information, which has led to several surprising discoveries in last two decades or so. The subject of Quantum Information is quite vast, and very broadly deals with topics such as Quantum Computing, Quantum Cryptography, Quantum Entanglement, New protocols for information processing and many more tasks which cannot be achieved classically [see for example: A. Zeilinger, *Phys. World* (March), 35-40 (1998)]. Here, we plan to give a brief overview of recent excitement in quantum computation and some fundamental limitations on quantum information.

Quantum Computation

Physics of information and computation are intimately related. Information is encoded in a state of a physical system. Computation is processing of information on actual physical system that obeys certain laws. Therefore, the study of information and computation are linked through a study of underlying physical processes. If the physical processes obey the rules of classical physics, the corresponding computation is classical. If the underlying processes are subjected to quantum mechanical rules, the resulting computation will be "*quantum computation*". The logic that lies at the heart of ordinary computers and quantum computers is completely direct. Quantum computation is a particular way of processing information which utilises principle of linear superposition, quantum entanglement and quantum measurement.

In conventional computers (present-day-computers) information is stored in bits such as 0's or 1's. To represent a bit, i.e., 0 or 1 one can use any physical system like a voltage in a circuit is at zero or at a positive bias, or current in a circuit in positive or negative direction, or by saying that a switch is on or off. A two bit information can be in any one of the $2^2 = 4$ possible states (e.g.00; 01; 10; 11). A three bit information can be in any one of the $2^3 = 8$ possible logical states (e.g. 000; 111; 011; 110; 101; 001; 100; 010). An *n* bit information can exist in any one of the 2^n possible logical states one at a time. Information stored in these binary digits can be manipulated using elementary logic gates that obey Boolean algebra. For example, in a classical computers one can manipulate information using sequence of logical operations such as AND, OR, NOT, and XOR gates. Computations that are done in our desk top computers basically use these logic gates.

Quantum Bit or Qubit

Suppose we represent a bit 0 or 1 by saying that the spin of a neutron is up or down, or we could say an atom is in ground or in an excited state, or a photon is horizontally or vertically polarized. All these systems are called two-state quantum systems because they can remain in any of these two logical states. Therefore, when a photon is in a definite polarization state it carries classical information (as it represents a 0 or a 1). However, quantum theory also allows a state of a spin-half particle, which is in a linear combination of spin up and down. This implies a new possibility for representing information by a two-state quantum system which can be both 0 and 1, i.e., a state of the type $\alpha|0\rangle+\beta|1\rangle$ with α and β being complex numbers in general and $|\alpha|^2 + |\beta|^2 = 1$. (According to Dirac a quantum state is denoted by a ket $|..\rangle$, which for a two-state system is a column matrix with two entries). This is called a quantum bit or 'qubit'. As we will see in subsequent section an arbitrary qubit contains a large amount of information. It is possible to design several new type of logic gates acting on qubits which can perform many computational tasks in parallel (due to linear superposition principle) which cannot be realised with classical computers [D. Deutsch, Proc. R. Soc. London. A, **400**, 97-117 (1985)]. One may recall that it is this linear superposition that lies at the heart of interference of quantum particles when they are made to pass through a Young's double slit experimental setup.

Quantum Register

It is a collection of qubits on which a program is to be executed. For example, if we have two qubits, they can exist in four logical states 00; 01; 10 and 11 and they can also exist in a *linear superposition of all four logical states*. In the latter case a typical state will be $\alpha|00\rangle+\beta|01\rangle+\delta|10\rangle+\gamma|11\rangle$. If there are *n* qubits they can exist in any one of the 2^n possible logical states and also can exist in a linear superposition of all 2^n logical states. This latter property in case of two or more quantum systems can give rise to quantum entanglement (intertwinedness). A composite state is entangled if it is not a product of individual states. A simplest example of entangled state is Einstein-Podolsky-Rosen state $1/\sqrt{2}(|01\rangle-|10\rangle)$ for two qubits which is familiar spin-singlet for two spin-half particles. In this state there is equal probability of finding the spins (ups and downs) for two qubits. Further, if spin of one particle is found up then the other is in down state. If two particles are in an entangled states then measuring one will affect the other instantaneously even though they are far separated in space. Spatial distance is immaterial because there is correlation in internal degrees of freedom. One can imagine that 'somehow' two particles love so much that even if they are far apart, still they are in contact! Physicists are still trying to understand the mechanism of this 'somehow'.

Quantum Parallelism and Quantum Algorithm

Like in a classical computer, to run a program in a quantum computer (QC) algorithms have to be devised. Algorithms on a quantum computer can be implemented by sequential application of quantum logic gates, which are nothing, but a set of unitary operations on n quits. An important result in this area is that any arbitrary operation ($2^n \times 2^n$ matrix) on n-qubits can be designed from single-qubit operator (2 x 2 matrix) and two-qubit operators (4 x 4 matrix).

The striking feature of QC is its computational potential – called "quantum parallelism". Suppose there is a black box that computes a function from an input bit x; ($x = 0; 1; .... 2^n$), i.e., it takes a single bit x to a single bit f(x). Classically one has to do $N=2^n$ function evaluations. But quantum mechanically all the N function evaluation can be done in one go because a QC can remain in a superposition of all N possible logical states (see fig 1). However, to know the answer we have to do a measurement on the output register and that will destroy the coherence. The result will be obtained according to certain probabilities. Thus it is a highly non-trivial task to design a quantum computer and get an answer for a desired problem.

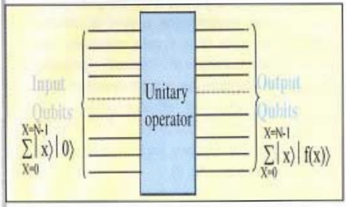

Fig.1 Parallelism in quantum computing: if a unitary operator U takes $|x\rangle|0\rangle \rightarrow |x\rangle|f(x)\rangle$*, with x=0,1,.....N, then a single action of U on equal superposition of logic states evaluates the function for all possible inputs of x.*

But why is it so interesting? It is not that a QC can solve some problem which cannot be solved in a classical computer (though this question is still an open). A quantum computer can solve all those problems that can be done on a classical computer. In addition, it can solve computationally hard problems with ease. 'Computationally hard' is measured through computational complexity – which says how the number of steps *s* required in a computation scales with the size of the input. If we feed an input number *N*, the information or length of the input is $L = \log_2 N$. If *s* is a polynomial function of *L* (such as say $s \approx aL + bL^2$), then the problem is tractable and if *s* grows exponentially with *L* (such as say $s \approx \exp[f(L)]$, where *f(L)* is some non-exponential function of *L)*, then the problem is 'hard'.

In recent years there have been three important algorithms discovered. One is the Deutsch-Josza (DJ) algorithm where one aims to know some 'global' information about a binary function *f(x)*, i.e., to know whether the function is balanced or constant. A balanced function is one which is 0 for half of the case and 1 for other half or vice versa. A constant function is one which is either 0 or 1 for all values of *x*. Since *x* takes *N* possible values a classical computer will take O(N) steps to decide it. But Deutsch and Jozsa found an algorithm on a quantum computer which can decide it in one step! So there is an exponential speed-up in a quantum computer [D. Deutsch and R. Jozsa, *Proc. R. Society (London)*, Ser. A **439** (1992) 553]. The second is the Shor algorithm where one aims to factorise a composite (a non-prime) number *x*. In general it is an intractable problem. In a classical computer the best known algorithm takes an exponentially large number of steps. Shor discovered that a QC can do the job in a polynomial number of steps. For example, to factor a number of size $L \sim 600$, the number of steps it takes is $s \sim 10^{25}$. It will take million years in a classical superfast computer but a quantum computer can do the factorisation in $s \sim 10^8$ steps, i.e., in few seconds! Shor's algorithm is one of the land-mark papers in quantum computation that generated a widespread interest among physicists, computer scientists, mathematicians and others alike [P. Shor, *Proc. 35th Annual Symp. on Found. of Comp. Sci.* IEEE Computer Society Press, 1994]. The third is the Grover algorithm, where one aims to find one particular item from a large unsorted data base containing *N* items. Classically, one needs to search *O(N)* times to find a particular item but quantum mechanically one can search in $O(\sqrt{N})$ steps [L. K. Grover, *Phys. Rev. Lett.* 79 (1997) 325]. There is a square-root improvement (i.e., the speed-up is polynomial) which can be a great advantage for large data base searches. For example, to find a person's name in a directory containing 10^8 entries, a classical computer will take so many steps whereas a quantum computer can do only in 10^4 steps.

These discoveries are important not only for physicists but also for computer scientists because they provide radical way of thinking about computation, information, and programming in general. It is worth mentioning that DJ's and Grover's algorithms have been implemented on `primitive quantum computers'. There have been various proposals to build a quantum computer but a full scale QC is far from scene. The experimental proposals include isolating and manipulating qubits in ion traps, solid state based devices such as SQUIDS, quantum dots, NMR techniques and many more [see for latest progress in experimental QC: *"Scalable Quantum Computers"* by H. K. Lo and S. L. Braunstein (Eds), Wiley-VCH Publisher, 2000].

Fundamental Limitations on Quantum Information

As we have discussed, qantum computation is a certain way of processing quantum information to achieve startling speed-ups in some class of problems. But there are much more amazing tasks one can do with quantum information. On the other hand there are some limitations on quantum information too. Therefore, it is important to know what type of operations are allowed in quantum world and what are not. These limitations are sign posts on the progress road of quantum information. In future when we build quantum information processing units we would know what type of machines we need to design.

Knowledge of a Quantum state

Quantum information has certain unique properties, which distinguish it from their classical counterpart. The *'knowledge'* of a quantum state is very crucial in deciding what operations one can do and what cannot. There is a vast difference between the information content of a quantum state being 'known' and `unknown'. But classically the information about a state can be known in principle. We know that in classical world the state of a particle is described by its position and momentum and there are no fundamental limitations on the precision with which we can measure these variables. Therefore, even if we do not know the state of a classical particle, we can always design an apparatus which can measure its state precisely without disturbing the particle. However, in the quantum world a state of a particle is not described by its position and momentum but by a wavefunction (in abstract 4 notion it is a state vector in a complex, linear, complete vector space called a Hilbert space). An important question is can we `know' the state of a particle if we are given just a single quantum system? The answer is `no'. To determine the state of a system completely one needs infinite number of identically prepared particles. For example, for a qubit described by a state $|\Psi\rangle = \cos\frac{\theta}{2}|0\rangle + \sin\frac{\theta}{2}e^{i\phi}|1\rangle$, if we say '*we know the state*' – this means, we know precisely the value of θ and ϕ (see fig. 2).

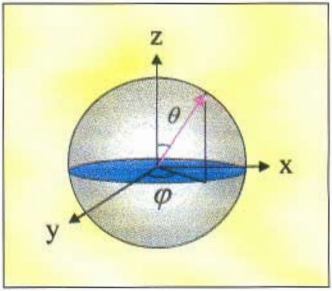

Fig 2. Geometrical way of representing a qubit on a Bloch sphere. All the points on this sphere represent possible states of a qubit. The tip of the arrow representing the point is a qubit parametrised by polar angle θ and azimuthal angle φ.

That is to say we `*know*' the exact point on the Bloch sphere. This is possible only when we have prepared the qubit ourselves by a suitable machine. But if some one else has prepared the qubit and given it to us, then the qubit is '*unknown*' to us. What it means is that we do not know the value of two real parameters θ and ϕ, and if we do not know them, there can be infinite number of possible value that they can assume. In other words if we do not know the exact point on the Bloch sphere, the point can lie any where (which has infinite number of possibilities). Therefore, *to specify an unknown qubit one needs infinite number of bits* (which is nothing but logarithm of number of possibilities). On the other hand we do not need any extra bits to specify a *known* qubit, because we have the complete knowledge (i.e. we do not lack any information).

One may wonder is it not possible to extract the information about the unknown numbers θ and ϕ by measurement? But if one performs measurements on a qubit one will get only two possible outcomes, i.e., it will project either to $|0\rangle$ or $|1\rangle$ with probability $\cos^2\frac{\theta}{2}$ and $\sin^2\frac{\theta}{2}$, respectively. Therefore, one can extract only one bit of information ($\log_2 2 = 1$) by a measurement! Moreover, after a measurement the state of the qubit is no longer the same. It has irreversibly changed to one of the two distinct states. This is a riddle of quntum information: even though an unknown qubit contains infinite amount of bits one can extract only one bit of information. Surprisingly, this '*unknowability*' of a quantum state has important implications in quantum information processing. It is precisely this nature of a quantum object that prohibits us to copy a quantum state, to delete a copy from two copies or to a state to its orthogonal state and many more.

No-cloning principle

We know that in classical world all information can be copied perfectly. A pedagogical (but crude) example is an ordinary xerox machine, where we feed a page containing some classical information and few blank sheets at input port and at the output port we get two or more copies. The xerox machine is 'universal' in the sense whatever information you feed you will get exact copies of an input. Moreover, the company which has designed a xerox machine does not know what information we will be copying. This means the information at users hand is apparently unknown to the person who has designed a xerox machine. Yet, it works equally well for all classical information. This is one example, which shows that in the classical world it possible to produce exact copies (in fact as many as we want) of any information. The other example is in a conventional computer we can always copy bits of information. This can again be done by designing suitable logic gates such as controlled NOT (CNOT) gates. A CNOT gate, for example, takes two bits as an input and produced two bits at the output such that the second bit is flipped if and only if the first bit is 1 (i.e.; 00 → 00; 01 → 01; 10 → 11; 11 → 10). Take 0 and 1 as inputs and 0 as a blank bit then by applying CNOT one can get 00 → 00 and 10 → 11, which is a copying operation. Everybody is familiar with making copies of some files in an ordinary computer.

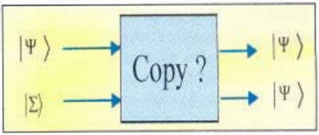

Fig.3 Quantum xerox machine

But can one design a xerox machine for a quantum state that will produce an exact copy of an '*unknown*' state? Surprisingly the answer is no. *We cannot copy an unknown quantum state!* This is a consequence of linearity of quantum evolution discovered by Wootters, Zurek and Dieks [W. K. Wootters and W. H. Zurek, Nature **299** (1982) 802; D. Dieks, *Phys. Lett. A* **92** (1982) 271]. In quantum worlds copying process for an 'unknown' qubit would involve the following action $|\Psi\rangle|\Sigma\rangle \rightarrow |\Psi\rangle|\Psi\rangle$, where $|\Psi\rangle$ is the state of the qubit, $|\Sigma\rangle$ is the blank state (analogous to blank paper in a xerox machine, see fig. 3).

If a qubit is in any one of the orthogonal state $|0\rangle$ or $|1\rangle$, then it carries classical information and one can design a xerox machine that can copy it perfectly. For example, a photon in a horizontal or vertical polarization state can be copied perfectly. But when a qubit is in an arbitrary linear superposition of two distinct bits then the machine fails. However, if we '*know*' a qubit we can copy it perfectly. No-cloning principle is in agreement with established principles. For example, if we could clone an unknown state perfectly then by making two sets of identical ensembles one can measure position on one and momentum on the other precisely. This will allow us to measure two conjugate properties of a system, which, in turn violates Heisenberg's uncertainty relation. Moreover, if we can clone an arbitrary state then using spin-singlet entangled state one can send signals faster than light. Because Alice at one end can measure her particle onto two orthogonal basis (she can get **1** bit) and Bob at the other end can use a cloning machine to produce infinite number of copies of his particle and can infer the measurement out come of Alice. This will allow a communication of **1** bit faster than light. But we know that we cannot send signals faster than light and this is another reason why cloning of 'unknown' states must be an impossible operation.

No-deletion principle

Yet, another fundamental limitation on quantum information has been discovered recently. In classical information theory deleting copies of some information is always possible using a CNOT gate. However, in quantum theory the perfect deletion of an unknown state from a collection of two copies is an impossible operation [A. K. Pati and S. L. Braunstein, *Nature* **404** (2000) 164]. To understand this question better imagine that there are two persons Alice and Bob. Alice prepares two copies of a qubit and gives to Bob. Now the information about the qubit is *known* to Alice but *unknown* to Bob. Then Alice asks Bob to design a deletion machine. Can Bob design a all purpose deletion machine? Not so. The very basic structure of quantum theory puts strong limitations on the complete deleting of the quantum information of an *unknown* state.

Here one should distinguish the process of erasure from deletion. Classically, erasure refers to getting rid of last bit of information from a collection of *unordered bits* whereas deletion refers to resetting the last bit to a standard bit from a collection of *identical ordered bits*. Classical deletion takes an ordered set of bits to another ordered set of bits and this is logically reversible. But erasure is an irreversible operation. In classical information theory there is Landauer's principle of erasure, which says that if you throw away one bit of information it must dissipate energy $E = kT \log 2$ at temperature T. Thus erasure of a single bit leads to increase of entropy of the surrounding by an amount $k \log 2$.

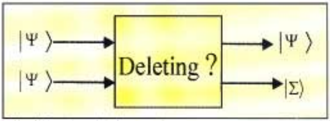

Fig. 4 Quantum deleting machine

The quantum deletion is fundamentally different than erasure [W. H. Zurek, *Nature*, **404** (2000) 130] Quantum deletion as defined aims to create a blank state and original copy states from two copies by a linear operation acting jointly on all the copies. For example the deletion process would take two copies of an unknown neutron or photon and produce a blank state together with the original copy. If we have two photons with arbitrary polarisation in some state $|\Psi\rangle$, the action of deleting machine can be represented as (see fig.4) $|\Psi\rangle|\Psi\rangle \rightarrow |\Psi\rangle|\Sigma\rangle$.

It was proved that though the above machine can work for qubits in orthogonal states but for an arbitrary qubit the above process does not exist. By linearity one can show that the final output states are different in ideal case and actual case. *Therefore linearity does not allow deleting of an unknown quantum state against a copy.* This principle is now called "quantum no-deletion" principle. Nevertheless, if one knows a qubit one can delete a copy. This is not just reverse of no-cloning principle, but an independent principle by itself. It is worth mentioning that in classically world one can erase and delete information (both the operations are allowed) but in quantum world one *cannot delete* but can only *erase* information at some energy cost.

The important implication of no-cloning which was discovered some twenty years ago is realised in recent years. Similarly, the implication of no-deleting principle discovered only last year will be realised in times to come. It is a hope that this may have some applications in the quantum computer and in general other quantum information processing units.

No-flipping principle

We know that classical information consisting of bits such as 0 or 1 can be i.e., 0 goes 1 and 1 goes to 0. This can be achieved by a using a NOT gate. Similarly, in quantum world a qubit in a prefered logical state $|0\rangle$ or $|1\rangle$ can be flipped because they again carry classical information. But can one flip an *unknown* qubit which is in an arbitrary superposition of two distinct logical states? Operationally, one can represent the flipping action as $|\Psi\rangle \rightarrow |\overline{\Psi}\rangle$, where $|\overline{\Psi}\rangle$ is orthogonal to $|\Psi\rangle$.

The answer to the above question is again 'no'. The reason behind such an impossibility is that we do not know the exact location of the point on the Bloch sphere. The flipping operation is nothing but inversion of the Bloch sphere. If we know the qubit, then we know the exact location of the point on the Bloch sphere and we can apply a rotation operator to get the flipped state. When the point on the Bloch sphere is unknown we cannot chose the NOT gate appropriately. Therefore an unknown qubit cannot be i.e., there is no universal-NOT gate for a qubit [V. Buzek, M. Hillery and R. F. Werner, *Phys. Rev.* A **60** (1999) R2626]. Surprisingly, if one picks up qubits from equatorial or polar great circles on a Bloch sphere then it is possible to design a NOT gate. This means that any point from these special class of states can be flipped exactly. With a priori information about qubits, even if they are unknown still they can be flipped exactly [A. K. Pati, *Phys. Rev.* A **63** (2001) 014302].

The physical reason behind such impossible operations is traced to our 'ignorance' about the qubit. This quantum ignorance is not just a practical one but of *fundamental one which cannot be removed at any cost.* However, the classical ignorance can always be removed in principle by suitable measurements. Hence, there are no limitations on copying, deleting or of classical bits.

Applications

The impossibility of 'knowing' a quantum state has important applications in *quantum cryptography.* Cryptography is an art of sending secret information between two parties. Usually, the security of classical cryptographic protocol depends on unproven assumptions about complexity of the retrieving the key. Bennett and Brasard [C. H. Bennett and G. Brasard, *Proceedings of the IEEE Conf. on Computers, Systems and Signal Processing*, Bangalore, India: IEEE, 1984, 175] were the first to realise that by encoding bits in quantum states Alice can send confidential information to Bob. A third party Eve, cannot know what message is sent from Alice to Bob because she cannot know the quantum state completely, nor can she make copies of the quantum states. In case she tries to read the information by measurement there will be 'unavoidable disturbances in the message and Bob will come to know that there was a spy! So the security to cryptography is provided by no-cloning principle and the laws of quantum mechanics. Quantum cryptography may play an important role in defence applications such as sending secret information across boarder regions where absolute security is essential.

Quantum information processing is not only limited to quantum computation, quantum cryptography but many other protocols which are impossible classically. Some of those are quantum teleportation (a method to send an object without physically sending it but the cost of destroying the original), entanglement swapping (a method to create quantum entanglement between two particles which have never interacted), remote state preparation (a method to prepare certain class of qubit at a distant laboratory), and so on. In recent years considerable progress has been made by leading scientists all over the world (though in India it is yet to gain momentum). The future challenge lies in discovering new quantum algorithms, new limitations, and building quantum information processors that will ultimately transform the living style of human civilisation in twentyfirst century and the society as a whole.

SCIENTISTS VISIT AQUACULTURE FARMS AND FISH PROCESSING UNITS

A team of scientists from the Food Technology Division led by Dr D.R. Bongirwar, Head, Food Technology Division, BARC, visited shrimp farms and fish processing units at Vishakapatnam and Kakinada to educate the farmers and processors on the usefulness of radiation processing for fish conservation and hygienisation. Dr K.R. Prasad, President, Confederation of Indian Aquaculture Farmers Welfare Association, arranged a meeting of aquaculturists, quality control officers, processors and officials including those from Central Institute of Fisheries Technology (CIFT) and MPEDA, Vishakapatnam, at the Conference Hall of Hotel Meghalaya, Vishakapatnam.

Dr D.R. Bongirwar, Head, Food Technology Division, BARC, and his team of scientists at the meeting at Vishakapatnam.

After the welcome speech by Dr Prasad, Dr D.R. Bongirwar gave a talk on the applications of radiation for food preservation. This was followed by Dr S.B. Warrier, who spoke on the preservation and hygienisation of seafoods using gamma radiation. Dr V. Venugopal talked on the importance of value addition in seafoods. Dr Ms Kamat and Dr J.R. Bandekar dealt in detail on the microbiological and plant quality management aspects of seafood irradiation, respectively. These presentations were followed by a lively discussion on the topic.

A general opinion emerged after the discussion was the need for mandatory irradiation of seafoods for their conservation and hygenization. Participants of the meeting were of the opinion that all efforts should be made to persuade Andhra Pradesh State Government to set up a radiation processing plant for seafoods in the coastal area of Andhra Pradesh. Dr Prasad emphasized the need for arranging an awareness workshop on radiation technology in fish processing industry for the benefit of seafood processors, quality control inspectors and aquaculture farmers. This workshop could be organized by BARC along with fisheries institutions including the Marine Products Export Development Authority.

NATIONAL SYMPOSIUM ON ENVIRONMENT

Environmental Assessment Division of BARC organised the 10th National Symposium on Environment at BARC during June 4-6, 2001. Dr V. Venkatraj, Director, Health, Safety and Environment Group, BARC, welcomed the delegates. Inaugurating the symposium, whose focal theme was "Environmental Implications of Electrical Power Generation", Dr Anil Kakodkar, Chairman, Atomic Energy Commission and Secretary, Department of Atomic Energy, highlighted the total commitment of the DAE to the environmental safety programme in all its activities. Dwelling on the strong R&D base in DAE in environmental sciences, training programmes and appropriate regulations, he told that radioactive releases from all our installations very well meet the national and international standards and efforts are on to achieve 'zero discharge' level.

Dr V. Venkat Raj, Director, Health, Safety and Environment Group, BARC, delivering his welcome address during the symposium. Others on the dais are (from left to right) : Dr S. Sadasivan, Head, Environmental Assessment Division, BARC, Mr B. Bhattacharjee, Director, BARC and Dr Anil Kakodkar, Chairman, Atomic Energy Commission and Secretary, Department of Atomic Energy.

Presiding over the inaugural session, Mr B. Bhattacharjee, Director, BARC, also stressed on the highest priority given to the environment and sustainable development since the very inception of nuclear facilities in our country. He pointed out that the *per capita* consumption of power in India is very low compared to developed countries. As the thorium and uranium potential in India is 10 times more than that of the fossil fuels, he said that nuclear power with highly developed infrastructure can enhance the availability of power while giving due regard to the environment.

In his welcome address and later in the invited talk on "Electricity Generation: Safety and Environmental Impact", Dr V. Venkat Raj, Director, Health, Safety and Environment Group, BARC, stressed that sufficient availability of affordable power is a prerequisite for economic development. Comparing different power generation options and their inherent safety and environmental implications, he said that thermal power is the main source of energy for the immediate future, but nuclear energy offers an environment friendly and sustainable option to meet our long term energy needs. Dr S. Sadasivan, Head, Environmental Assessment Division, BARC, proposed a vote of thanks.

There were nine invited talks by eminent experts on a variety of topics on power generation options, natural radioactivity, analytical techniques, biological impact of thermal discharges, role of nuclear energy in green house gas mitigation, techniques used in environmental management and impact assessment and role of remote sensing. A total of 51 contributing papers were presented. In an evening lecture on 4th, Mr V.K. Chaturvedi, Chief Managing Director, NPCIL traced the history of nuclear power programme in India and dwelt on its strength, expertise gained and ability to meet future challenges. About 200 delegates from different DAE units and other institutions including several universities and colleges participated in this symposium.

A number of industries manufacturing environmental related systems participated in an exhibition organised along with the symposium and exhibited their products.

BARC SCIENTISTS HONOURED

- Dr J.P.Mittal, Director, Chemistry & Isotope Group, BARC, was presented the Golden Jubilee Commemoration Medal for Chemical Sciences (2001). The medal is awarded once is three years for outstanding contributions to chemistry. Eminence of the awardee is fudged with the criterion that the scientific work of the candidate in such that its impact has been felt for a considerable length of time.

The medal will be awarded to Dr Mittal later this year during his award lecture.

- Dr S. Adhikari of Radiation Chemistry & Chemical Dynamics Division has been selected as one of the 5 winners of the 2001 IUPAC Prize for Young Chemists. This award is given on a global competition basis to 5 young chemists for the best Ph.D. thesis submitted to the University. Dr Adhikari submitted his Ph.D. thesis "Radiation chemical studies on biological and other important molecules in micelles, microemulsions and aqueous solutions" to Mumbai University and got the Ph.D. degree under the guidance of Dr T. Mukherjee, Head, Radiation Chemistry & Chemical Dynamics Division, in the area of Radiation Chemistry and Micro-heterogeneous Systems. The award consists of US$ 1000/- and a free trip to the next IUPAC Congress to be held in Brisbane, Australia, during July 1-6, 2001. The awardee has to present the poster regarding his scientific contribution. The award will be made during the glittering opening ceremony on July 1, 2001. The Prize Selection Committee was chaired by distinguished chemist, Prof. Joshua Jortner of Tel Aviv University, who also is the past President of IUPAC.

- Mr V.M. Bhole of Atomic Fuels Division, BARC, has been awarded the National NDT Award 2000 in the Research and Development category. He is the leader of the eddy current testing group in NDT & QE Section.

Some of the important contributions of Mr Bhole are as follows: (i) In-service inspection of coolant of PHWRs, including detection of titled garter spring, PT/CT gap measurement, oxide layer thickness measurement on ID of coolant tube, flaws detection on ID of coolanta tube, and development of the computer eddy current test system for in-service inspection of calandria tubes. (ii) Testing of nuclear fuels, (iii) Characterisation of hydride blister on zircaloy pressure tube for PIE, and (iv) In-service inspection of heat exchanger and steam generator tubes in Heavy Water Plants, Power Reactors and in some Fertiliser plants.

- Dr Pitamber Singh, Head, FOTIA Section, Nuclear Physics Division, BARC, has been selected as member of the National Academy of Sciences, India. Dr Singh has made an outstanding contribution in setting up the 6MV Folded Tandem Ion Acelerator (FOTIA) facility at BARC which is an accelerator of its own kind amongst a few in the world.

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