10.6 The TARC Experiment at CERN: Modern Alchemy

Jean-Pierre Revol

TARC, which stands for Transmutation by Adiabatic Resonance Crossing, was the idea of Carlo Rubbia to make use of the unique properties of lead to enhance, by orders of magnitude, the transmutation rate of long-lived fission fragments, such as ^{99}Tc and ^{129}I (two elements that represent 95% of the radio-toxicity of long-lived fission fragments in nuclear waste). Conversely, the same method may be applied to produce radioisotopes from stable elements, using accelerator-driven systems (ADS) instead of nuclear reactors. The goal of the TARC experiment (PS211), proposed at the CERN PS in 1995 [45], and carried out in 1996 and 1997, was to demonstrate the feasibility of these two attractive possibilities.

The physics of TARC is rather simple and based on a unique combination of properties of neutrons produced inside a volume of lead. Lead is an excellent material for the production of spallation neutrons through the impact of a proton beam; it is an element with one of the lowest cross-sections for neutron capture; it has a short elastic-collision length, $l_0 \approx 3$ cm; and it has a large nuclear mass compared to the neutron mass, which leads to an average fractional neutron energy loss in an elastic collision, quantified by the lethargy coefficient η_0, that is very small, $\sim 9.7 \times 10^{-3}$. In this low-lethargy medium, time and velocity are strongly correlated, such that there is a simple relation between velocity, v, and time ($t \approx 2l_0/\eta_0 v$). In this way, the time at which a neutron is observed in the experiment is correlated with its velocity and, hence its kinetic energy, providing a simple way to determine energy from time measurements [46].

Because of the very low neutron-capture probability, in a sufficiently large volume of lead a 1 MeV spallation neutron will survive for a long time, typically 3 ms, undergoing 1800 scatterings along a 60 m path, before it is eventually captured as thermal energy. Neutrons of MeV energies thus slow down in lead through many very small energy losses. If some ^{99}Tc is incorporated in the lead, such neutrons are certain to go through the energy of a resonance in the neutron-capture cross-section of ^{99}Tc and so enhance by orders of magnitude the transmutation probability of ^{99}Tc, which is radioactive, into ^{100}Ru, a stable element. This process is referred to as adiabatic resonance crossing. The long lifetime of neutrons in lead and the small elastic-collision length have the additional effect of increasing the neutron flux locally, as a neutron is likely to cross the same elementary surface several times during its random walk.

In the TARC experiment, these expected properties of neutrons in lead were beautifully verified with high precision in 334 tonnes of pure lead installed in a CERN PS proton beam line. It was particularly important to check that a sufficiently large fraction of neutrons would survive the capture resonances of lead and reach the capture resonances of interest, for the destruction of long-lived fission fragments (Fig. 10.9). Using $^{6}Li/^{233}U$ target silicon detectors, ^{3}He ionization detectors, and many activation methods, the TARC collaboration measured with unprecedented precision neutron fluxes over neutron energies covering eight orders of magnitude [47].

Tests of transmutation of ^{99}Tc and ^{127}I carried out at various locations inside the lead volume of the TARC experiment, validated both the TARC method and the simulation developed specially for the Energy Amplifier studies [16]. The simulation can therefore be trusted to predict the performance of an industrial system either to destroy long-lived fission fragments or to produce radioisotopes for nuclear medicine and other industrial applications. It was shown that in an Energy Amplifier in which ^{99}Tc or ^{127}I have been diluted in the lead volume, it is possible to destroy these elements at about twice the rate at which they are produced in nuclear reactors [47].

The TARC collaboration also measured the production rate of ^{99m}Tc, an isomer of ^{99}Tc, the most widely used radioisotope in medicine, from the activation of natural molybdenum, and confirmed the feasibility of an industrial activator for

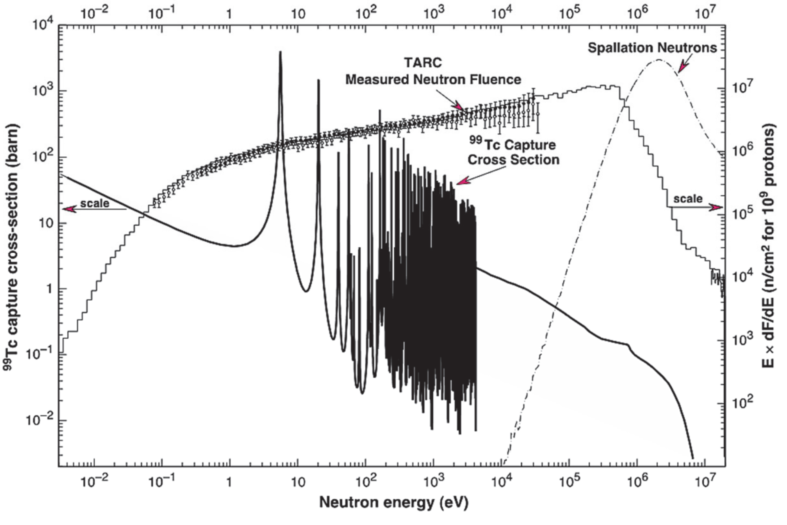

Fig. 10.9. The flux of relatively high energy spallation neutrons (dashed line) is transformed into a neutron flux covering many orders of energy. The resonances in the capture cross-section of ^{99}Tc cannot be missed, as the average energy loss of a neutron through elastic scattering is typically smaller than the width of resonances. Data points are taken from TARC neutron flux measurements for 3.5 GeV/c protons [47]. The histogram (full thin line) is the neutron flux obtained with the TARC simulation [47]. The ^{99}Tc neutron capture cross-section (full thick line) [48] exhibits two most prominent resonances at 5.6 eV and 22.3 eV.

the production of such an element, or of other radioelements used in medical imaging, diagnostics, and therapy. As a result, CERN took a patent [49] on the TARC idea, and various industrial pharmaceutical companies showed interest in its exploitation. The patent, valid until 2017, is very much of interest, as the demand for ^{99m}Tc has exploded and new therapies based on lutetium, rhenium, holmium, etc. are in rapid development.

The TARC experiment was a landmark experiment, which studied the phenomenology of neutrons in lead. It showed that ADS may be used to destroy nuclear waste and provide an alternative to nuclear reactors in the production of radioisotopes. It validated an innovative simulation that is now used for the design of ADS. The TARC concept also led to the design and construction of the CERN neutron Time-Of-Flight facility, n_TOF [Highlight 3.9], with its high rate, high precision neutron flux and low background. It offers unique conditions for the measurement of neutron cross-sections, a necessary input to any reliable simulation and development of new nuclear systems.

10.7 A CLOUD Chamber with a Silvery Lining

Jasper Kirkby

During his first visit to the Ben Nevis Observatory in 1894, the future Nobel laureate C.T.R. Wilson became fascinated by clouds and the beauty of coronas and "glories" (coloured rings surrounding shadows cast on clouds). He returned to the Cavendish Laboratory in Cambridge determined to re-create clouds in the laboratory and study their physical phenomena. This led him to develop the expansion cloud chamber — a detector on which much of the experimental foundation of particle physics was built in the first half of the 20th century.

More than a hundred years later, a new cloud chamber is in operation at CERN. The CLOUD experiment is optimized to study the influence of cosmic rays on aerosols and clouds [50]. CLOUD reproduces atmospheric conditions in a large chamber (Fig. 10.10) to study aerosol particle formation and growth in controlled laboratory conditions. Clouds are generated by adiabatic pressure reductions of humid air parcels, as in Wilson's cloud chamber, but at the much smaller water vapour supersaturations found in natural clouds (a few times 0.1%, compared with around 500% for a Wilson cloud chamber). Depending on the air temperature and the nature of the seed particles, either liquid or ice clouds form.

The primary scientific goal of CLOUD is to answer the question of whether or not cosmic rays exert a climatically significant effect on aerosols and clouds, as suggested by satellite observations first reported in 1997 [51]. This intriguing