POLARIZED β EMITTERS FOR NMR PROBES

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The physical principles of atomic and nuclear polarization by the tilted-foil interaction as applied to the production of polarized β emitters for NMR probes are discussed.

1. Introduction

As described in detail in the previous papers, since 1965 Sugimoto and collaborators at Osaka developed a sophisticated NMR technique [1], which utilized as probes short-lived β-radioactive nuclei. This technique consists essentially of the following four procedures: (i) production of polarized, β-emitting nuclei; (ii) implantation of the β emitters into materials which can preserve the nuclear polarization during their nuclear lifetimes; (iii) detection of the nuclear polarization from measured β-ray asymmetry; and (iv) resonant destruction or reversal of the nuclear spin of the β emitter by use of rf magnetic fields (NMR).

To realize this technique, the initial creation of polarized β emitters for the later NMR studies is of crucial importance. In the early stage of development of this technique, polarized β emitters were mainly produced by nuclear reactions. By choosing suitable parameters, i.e. the incident-beam energy and reaction-product recoil angle, polarized β-radioactive reaction products were obtained. In the first historical experiment [1], the magnetic moment of $^{17}$F was successfully determined from polarized $^{17}$F nuclei, polarized via the $^{16}$O(d,n)$^{17}$F reaction at incident-deuteron energy $E_d = 2.3$ MeV and $^{17}$F recoil angle $\theta_R = 18^\circ$. Since 1965, in a series of NMR experiments by the Osaka group, the additional ground-state nuclear moments of $^8$B, $^{12}$B, $^{12}$N, $^{17}$F, $^{29}$P and $^{41}$Sc have been yielded after these isotopes were polarized in a similar manner [2].

At Stanford during the years 1974 to 1976, Minamisono extended the aforementioned NMR technique to other cases by use of polarization transfer from an
incident polarized beam to reaction products which through this process were polarized. Polarized proton and deuteron beams from the Stanford Tandem Van de Graaff bombarded targets which had the dual purpose of producing a nuclear reaction and acting as a recoil stopper for the (implanted) produced polarized β emitters. By this development, Minamisono et al. [3] at Stanford successfully determined the nuclear moments of $^{25}$Al, $^{31}$S and $^{39}$Ca, as well as the quadrupole moment of $^{8}$Li, all with β emitters.

The next extension of the technique at Osaka was to polarize other β emitters by means of the Overhauser effect in lithium metal. In this method, the β-radioactive nuclei are implanted into a thin film of lithium metal, which had previously been evaporated onto the inside wall of a microwave cavity resonator. By saturating the conduction electron-spin resonance of the lithium metal, impurity nuclei can be polarized by the Knight-shift interaction of the conduction electrons, in the same manner that the bulk-evaporated lithium metal nuclei are polarized, which is through relaxation of saturated conduction electrons back to thermal-equilibrium states. With this technique, the nuclear spin of $^{28}$Al was polarized, and the magnetic moment of $^{28}$Al [4] was determined more precisely than in previous experiments.

As another method of polarizing β emitters, it has been proposed by Minamisono [2,5] that nuclear-aligned but not polarized β-radioactive nuclei, which are more easily produced in nuclear reactions than polarized nuclei, can also be used for the NMR experiments by introducing a spin control technique. In the technique, selective rf transitions are induced among certain magnetic sublevels with are perturbed not only by a magnetic but also by an electric quadrupole interaction, resulting in conversion of nuclear alignment into nuclear polarization, or vice versa. This idea was successfully realized in the experiments on fundamental β-decay problems [6], where polarized $^{12}$B and $^{12}$N nuclei were converted into nuclear-aligned states, crucial to the experiments.

Since 1974, an unsophisticated and simple universal technique to polarize heavy ions has been developed in the field of atomic physics. The technique consists of two steps: (i) first, to create atomic polarization by passage of the ion beam through a tilted-foil surface; second, to transfer this atomic polarization to the nucleus by means of the hyperfine interactions during flight in free space. In principle, any nucleus ($I 
eq 0$) can be polarized by these steps, i.e. by use of a cheap, thin tilted foil (the tilted-foil technique).

The application of this technique to polarize β-radioactive nuclei seemed quite natural to us. Since 1980, in order to extend this technique to nuclear physics problems, cooperative research was undertaken between the Osaka group and the Århus group, who had already studied the technique by means of atomic physics methods. A description of the tilted-foil technique and experimental results with it are delineated in the following sections.