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Studying Matrix Elements for the Neutrinoless Double Beta Decay of ^{150}Nd via the ^{150}Sm(t,^{3}He)^{150}Pm* and ^{150}Nd(^{3}He,t)^{150}Pm* Reactions

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The existence of neutrinoless double beta decay would prove that neutrinos have a Majorana nature and that lepton number is not conserved. To extract information about the neutrino mass scale and hierarchy from $0\nu\beta\beta$ decay experimental data, accurate nuclear matrix elements are needed. Such information is also crucial for the design of experiments aimed at detecting neutrinoless double beta decay. Nuclear charge-exchange experiments play an important role in constraining the theories used to predict these matrix elements by providing Gamow-Teller strengths and higher order multipole transition strengths. The charge-exchange group at the NSCL focuses on the measurements of ^{150}Sm(t,^{3}He)^{150}Pm* and ^{150}Nd(^{3}He,t)^{150}Pm* reactions, which are of relevance for the double beta decay of ^{150}Nd. The details for the ^{150}Sm(t,^{3}He)^{150}Pm* experiment and the upcoming ^{150}Nd(^{3}He,t)^{150}Pm* experiment are discussed.

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1. Motivation

Double beta decay is a rare process that may occur in the absence of other allowed decay modes. Two-neutrino double beta decay [1] $(2\nu\beta\beta)$ has been detected for a number of different isotopes. Zero-neutrino double beta decay [2] $(0\nu\beta\beta)$ is not allowed in the standard model of particle physics. However, its existence is a matter of great interest, since a positive detection would prove neutrinos to be Majorana particles, break total lepton number conservation, and provide insights into CP conservation [3]. Numerous experiments with a variety of isotopes are planned or ongoing worldwide to search for $0\nu\beta\beta$ decay and to check the report of a positive signal by Klapdor-Kleingrothaus et al [4]. However, a measured half-life must be supplemented with other factors to successfully constrain the neutrino mass scale and hierarchy. There are 41 $\beta\beta$ isotopes [5] and only a handful of half-life measurements by geochemical, radiochemical, or direct methods have been made.

The decay rate for $0\nu\beta\beta$ decay is

$$[T_{1/2}^{0\nu}(0^+ \to 0^+)]^{-1} = G^{0\nu}(E_0,Z)|M_{GT}^{0\nu} + M_T^{0\nu} - \frac{g_V^2}{g_A^2}M_F^{0\nu}|^2\langle m_{\beta\beta}\rangle^2, \tag{1.1}$$

where $G^{0\nu}(E_0,Z)$ is a phase-space factor, $\langle m_{\beta\beta}\rangle$ is the effective neutrino mass, and $M_{GT}^{0\nu}$, $M_T^{0\nu}$, and $M_F^{0\nu}$ are the Gamow-Teller, tensor and Fermi matrix elements [6]. $G^{0\nu}$ can be calculated and is proportional to powers of the Q value of the decay and the proton number of the mother nucleus $(G \propto Q^5 Z^2)$. The nuclear matrix elements must be known to about 20% in order to provide useful information on $\langle m_{\beta\beta}\rangle$. In the $2\nu\beta\beta$ case the transition only proceeds through $J^\pi = 1^+$ states of the intermediate nucleus. However, $0\nu\beta\beta$ decay can proceed through intermediate states with varying J^π, which greatly complicates calculation of the matrix elements. Experimental efforts to populate the intermediate nuclei for $0\nu\beta\beta$ transitions are necessary to test theoretical calculations and reduce the error in the matrix elements.

2. Charge-exchange and $\beta\beta$ decay

Nuclear charge-exchange reactions are a valuable tool to extract the Gamow-Teller, Fermi, and higher isovector multipole strengths in energy ranges inaccessible to β-decay experiments. They probe the spin-isospin response of nuclei by exchanging a proton (neutron) in the projectile with a neutron (proton) in the target nucleus. At intermediate energies (E $\gtrsim$ 100 MeV/A) and vanishing momentum transfer (q = 0), the differential cross section for Gamow-Teller transitions is proportional to the Gamow-Teller strength: $\frac{d\sigma}{d\Omega}(q=0) = \hat{\sigma}B(GT)$ [7, 8]. Since the unit cross section can be calibrated using transitions of known Gamow-Teller strength from β-decay, Gamow-Teller strengths can be extracted from charge-exchange data in a model-independent way. The empirical strength distribution then can be used to test theoretical calculations employed for $0\nu\beta\beta$ and $2\nu\beta\beta$ decay [9, 10].

A large variety of charge-exchange probes are available, such as (p,n), (n,p), (d,^{2}He), (^{3}He,t), (t,^{3}He), and (^{7}Li,^{7}Be). This work focuses on the use of the (^{3}He,t) and (t,^{3}He) reactions to study charge-exchange on ^{150}Nd and ^{150}Sm respectively. The two reactions are similar: they both give

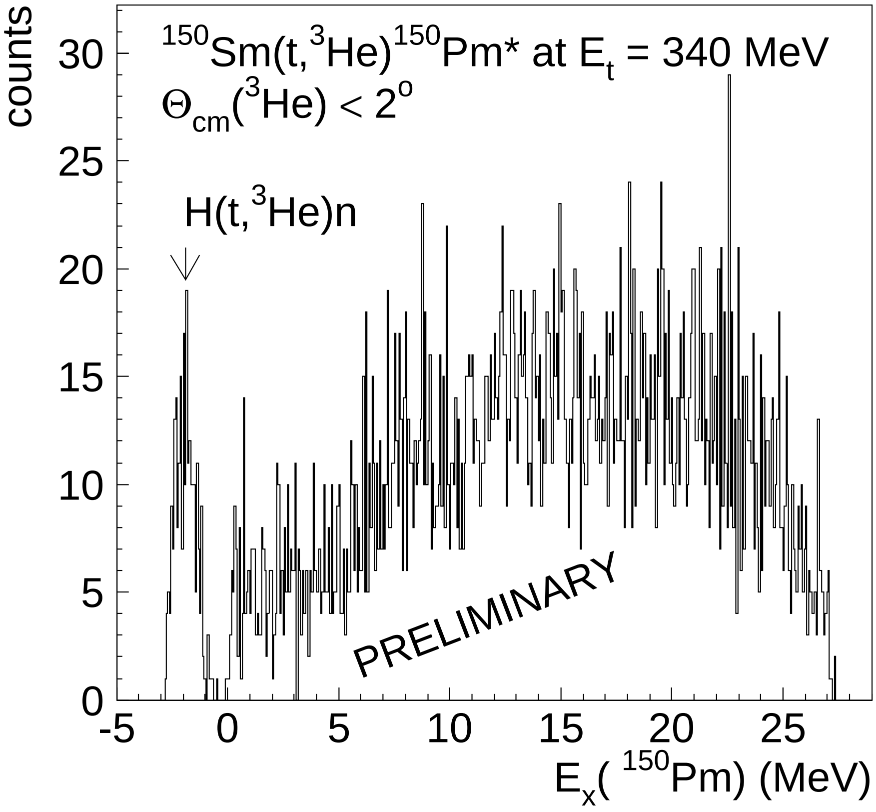

Figure 1: Preliminary excitation energy for the ^{150}Sm(t,^{3}He)^{150}Pm* experiment is shown for an angular range of 0-2°. The full experiment covered angles up to 5°. Contamination from hydrogen in the target (peak below 0 MeV) has not yet been removed. In the future, multipole strengths for ΔL=0, ΔL=1, and ΔL=2 will be extracted and the resulting Gamow-Teller strength compared with theoretical calculations.

good resolution ($\sim$30 keV for (^{3}He,t) and 200-300 keV for (t,^{3}He)) and allow for the determination of absolute cross sections. Recent charge-exchange papers that cite double beta decay as a primary motivation have looked at the nuclei ^{48}Ca [11], ^{64}Zn [12], ^{76}Ge, and ^{96}Zr [13]. Other such experiments are in progress.

3. The case for ^{150}Nd

^{150}Nd has a large Q value for $\beta\beta$ decay and a high proton number, which results in a large value for the phase-space factor G. As a result, it is an attractive candidate for $\beta\beta$ studies. However, it is also deformed. Deformation is expected to decrease the nuclear matrix element [14, 15], but the extent of the reduction is not well known. Other $\beta\beta$ decay candidates (including ^{76}Ge) exhibit some degree of deformation, so insight from experimentation and calculation on ^{150}Nd is also useful for the other candidates. Out of the 10-15 proposed $\beta\beta$ decay experiments [16], two (DCBA [17] and SNO++ [18]) use ^{150}Nd as their primary isotopes. MOON [19] has the potential to use ^{150}Nd as well. However, very little is known about ^{150}Pm, the intermediate isotope between ^{150}Nd and its $\beta\beta$ daughter ^{150}Sm, and information on the nuclear structure of ^{150}Pm is necessary to estimate $\beta\beta$ half-lives. To this end, two charge-exchange experiments were proposed and accepted: ^{150}Sm(t,^{3}He)^{150}Pm* at the National Superconducting Cyclotron Laboratory (NSCL) and ^{150}Nd(^{3}He,t)^{150}Pm* at the Research Center for Nuclear Physics (RCNP).

4. Experimental setup and status

The ^{150}Sm(t,^{3}He)^{150}Pm* experiment ran in February of 2008. A 115 MeV/u secondary triton beam [20] impinged upon a 2.5-by-7.5 cm, 18 mg/cm^{2} target of ^{150}Sm. The ^{3}He ejectile was detected in the focal plane of the S800 spectrometer [21, 22]. The S800 beamline is operated in dispersion-matched mode to achieve high resolution. A raytracing procedure [23] was used to reconstruct the scattering angles and momenta of the ^{3}He particles at the target from the measured angles and positions in the focal plane detectors of the S800. A missing mass calculation was done to find the excitation energy of ^{150}Pm. Figure 1 shows a preliminary excitation energy spectrum for six hours of ^{150}Sm(t,^{3}He)^{150}Pm* data. Analysis is ongoing. The ^{150}Nd(^{3}He,t)^{150}Pm* experiment is scheduled for December of 2008. It will use the high-resolution Grand Raiden spectrometer and its accompanying beam line [24]. The resulting Gamow-Teller and higher multipole strengths from the two experiments will be used to constrain theoretical calculations for the $0\nu\beta\beta$ matrix elements for the decay of ^{150}Nd in collaboration with theory groups.

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