Nuclear reactions with radioactive, isomer beams: Coulomb excitation of $^{18}F_{g.s.}$ and its $J^{\pi} = 5^{+}$ isomer $^{18}F^{m}$ using a large position-sensitive NaI array

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Abstract

Intermediate-energy projectile Coulomb excitation of the unstable nucleus $^{18}F_{g.s.}$ and its short-lived $E_x = 1.1$ MeV ($J^{\pi} = 5^{+}$) isomeric state ($t_{1/2} = 162$ ns) $^{18}F^{m}$ have been studied at 30 MeV per nucleon. Radioactive beams of $^{18}F_{g.s.}$ and $^{18}F^{m}$ nuclei were produced by nucleon transfer on a carbon production target and delivered to a secondary ^{197}Au target for Coulomb excitation. Photons emitted in the vicinity of the ^{197}Au target were detected in a large-solid-angle position-sensitive NaI(Tl) array, which allowed for the identification of the beam and target excited states populated by intermediate-energy Coulomb excitation. Two possible ^{18}F ground-state excitations were identified and $B(E\lambda\uparrow)$ values deduced. Upper limits were established for reduced transition probabilities $B(E1\uparrow)$ and $B(E2\uparrow)$ of several predicted transitions from the $^{18}F^{m}$ isomeric state, $5^{+} \rightarrow 4^{+}, 4^{-}, 3^{+}$, and compared with values inferred from γ-decay lifetimes. An indication of enhanced in-flight isomer decay, possibly due to the Coulomb interaction with the target is observed and discussed. The special detector configurations and analytical techniques needed for these types of measurements are described together with suggested improvements.

Keywords: Coulomb excitation; radioactive nuclear beams; position-sensitive γ array; isomer beams.

1. Introduction

Low- and intermediate-energy in-beam Coulomb excitation experiments [1,2] using radioactive nuclear beams (RNB) have been shown to be feasible and powerful tools in the study of nuclear structure of radioactive nuclei. We have used the intermediate-energy Coulomb excitation technique and a large solid angle position-sensitive NaI(Tl) array to study Coulomb excitation of ^{18}F and its short-lived 5^{+} isomeric state, $^{18}F^{m}$ ($E_x = 1.1$ MeV; $t_{1/2} = 162$ nsec).

Elements ($Z > 20$) are produced in astrophysical events such as nova and supernova through a process of rapidneutron capture (r-process) and this process can involve isomeric states which could act as "waitpoints" or bottlenecks to the production of heavy elements [3,4]. The nucleus $^{18}F^{m}$ (Fig. 1), while not directly involved in the r-process, serves as an excellent isomer for study.

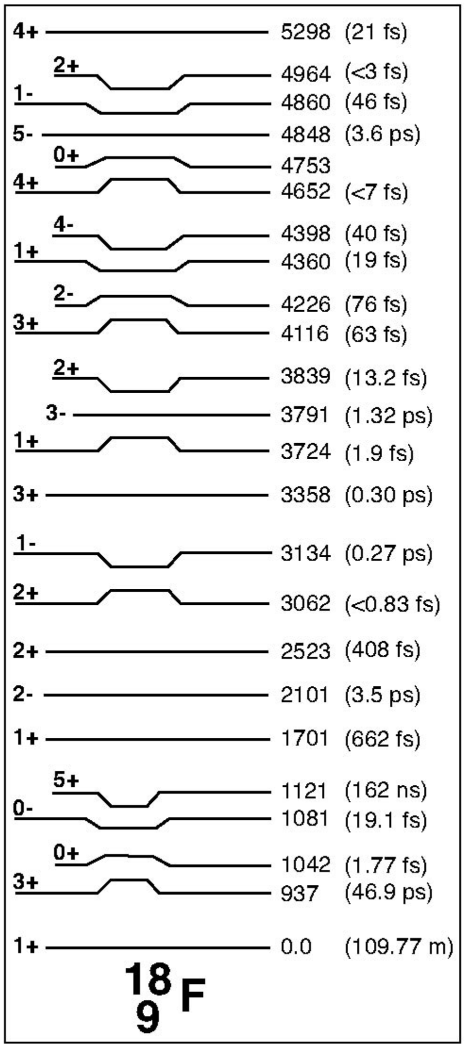

Fig. 1. A partial level scheme of ^{18}F is shown. The labels on the left of the figure denote the spins and parities of the energy levels whereas the labels on the right give the level energies in keV and the half lives. The $J^{\pi} = 4^{-}$ level at E_x = 6096 keV is not shown [9].

2. Experimental setup

A 45 MeV per nucleon ^{17}O beam, from the K1200 cyclotron at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University, irradiated a carbon production target located at the Dispersive Image 2 position of the A1200 fragment separator [5,6] thus maximizing the rate of $^{18}F^{m}$ at the target location. A fast plastic scintillator was used for timing the beam particles. The ^{18}F and $^{18}F^{m}$ ions were selectively produced using the $^{12}C(^{17}O,^{18}F)^{11}B$ proton transfer reaction. This reaction produces a copious amount of the high-spin, stretched (5^{+}) ^{18}F isomeric state ($^{18}F^{m}$) with high yield in the forward direction [5].

A schematic of the experimental apparatus is shown in Figure 2. A cylindrical fast-slow phoswich scintillator detector placed at the end of the experimental apparatus stopped the secondary beam fragments and was used for energy loss (fast plastic) and total energy (slow plastic) measurements at and near zero degrees. The stopping detector subtended a half angle, $\Delta\theta = 5.6°$, with respect to the excitation target (i.e. $\Delta\theta_{cm} \leq 6.1°$). The excitation target was comprised of two ^{197}Au foils (234.8 mg/cm^2 total) with an effective diameter of ≈ 4 cm. The excitation target was placed at the center of the NSCL position-sensitive NaI γ array. Energy loss and time-of-flight (TOF) was used for particle identification [6].

In this experiment, photons were emitted from an excited projectile moving at a significant fraction of the speed of light (typically on the order of β = 0.2 - 0.4), hence Doppler shift corrections must be applied. The NSCL NaI-detector array consists of 38 position sensitive NaI(Tl) detectors arranged in three concentric rings parallel to the beamline. Each detector is comprised of a NaI(Tl) crystal (5.75 cm dia., ≈ 18 cm length) enclosed in a 0.45 mm aluminum shield, optically joined to a photomultiplier tube at each end of the crystal. To shield against ambient γ-radiation, the entire array is surrounded by a 16.5 cm layer of low-background (pre-World War II) lead. The array was calibrated for energy, efficiency, and position using an appropriate set of γ-sources. Finally, measurements of in-beam Coulomb excitation of ^{12}C (Doppler corrected) and ^{197}Au target excitation (no Doppler correction needed) were performed and verified with known B(Eλ) values [6].

<<<Figure 2 Here (full page width)>>>

3. THE COULOMB EXCITATION OF $^{18}F_{G.S.}$ AND $^{18}F^{M}$

We note that in earlier experiments, the relative populations of nuclei in the $^{18}F_{g.s.}$ and the $^{18}F^{m}$ isomeric state were measured by a method of detecting the isomeric de-excitation γ-rays, a technique denoted as "isomeric-beam γ-tagging" [5-7]. In this experiment, the isomer population was monitored by measuring the yield of γ rays de-populating the isomer using a pair of HPGe γ-ray detectors located near the zero-degree detector (Fig. 2).

3.1. The Coulomb Excitation of $^{18}F_{g.s.}$

If we assume that the two distinct photopeaks observed in the projectile-frame spectrum of Figure 3 can be assigned to in-flight $^{18}F_{g.s.}$ Coulomb excitations, then the photopeak at 2.1 MeV could correspond to an E1 de-excitation of the known 2101 keV ($J^{\pi} = 2^{-}$, $t_{1/2} = 3.5 \pm 4$ ps) excited state in ^{18}F to the 1^{+} ground state. The width of the 2.1 MeV photopeak was measured to be 142 keV (7% FWHM). The photopeak at 2.5 MeV may be assigned to an E2 transition from the 2523 keV ($J^{\pi} = 2^{+}$, $t_{1/2} = 409 \pm 17$ fs) excited state to the 1^{+} ground state. These photons mostly should be due to $^{18}F_{g.s.}$ in-flight Coulomb-excitation events.

Assuming pure first-order Coulomb excitation, we infer a reduced "up" transition probability, B(E1 ↑; $1^{+}_{g.s.} \rightarrow 2^{-}$) of $(7.1 \pm 2.7)\cdot 10^{-3}$ e^2fm^2. Similarly, we extract a reduced "up" transition probability, B(E2 ↑; $1^{+}_{g.s.} \rightarrow 2^{+}$) of 5.5 ± 2.8 e^2fm^4 for the apparent Coulomb excitation of the 2523 keV

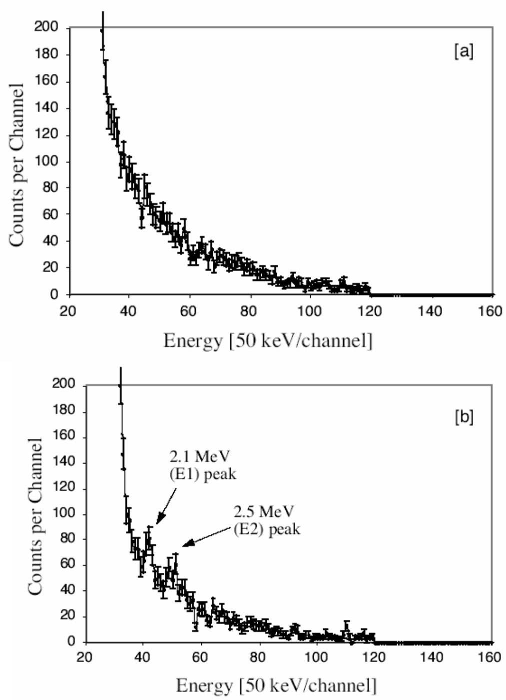

Fig. 3. Raw energy [a] and Doppler-corrected energy [b] spectra for the ^{18}F Coulomb-excitation data. Note the excitation photopeaks in the projectile ($\beta = 0.27$) frame that dissipate in the laboratory frame ($\beta = 0$).

excited state in ^{18}F. Our B(Eλ ↑) values have been compared to the reduced transition probabilities deduced from lifetime measurements. The value B(E1↑) deduced for the 2.1 MeV Coulomb excitation of the $^{18}F_{g.s.}$ is much larger (x10^3) than the value calculated from the experimentally-determined half life of the 2101 keV transition assuming pure E1↓ for the latter. Based on the known lifetimes of other levels in ^{18}F that could be excited via E1↑ or E2↑, we cannot unambiguously identify (within the limited NaI detector energy resolution) the origin of the observed photons near 2.1 MeV. ^{17}O beam contamination does not appear to be a likely source of the discrepancy. In contrast, the value of B(E2↑) deduced assuming the Coulomb excitation to the 2.5 MeV level from $^{18}F_{g.s.}$ agrees reasonably well with that predicted from the experimentally-determined γ-decay lifetime of the 2523 keV transition [8]. This is to our knowledge the first direct measurement of this reduced transition strength.

3.2. The Coulomb Excitation of $^{18}F^{m}$.

The present data allowed us to predict possible transition channels between the isomeric state and collective states built above the 1.1 MeV $J^{\pi} = 5^{+}$ isomer (Fig. 1) and in particular E1↑ transitions which, excluding nuclear structure and isospin considerations, could have been readily observable. These are listed in Table I.

TABLE I. Limits on reduced transition probabilities for Coulomb excitation of states possibly excited from the $J^{\pi} = 5^{+}$ isomer in ^{18}F.

Excited State Energy [keV]	J^{π}	Eλ	Transition Energy [keV]	Measured B(Eλ↑) Limit
4652	4^{+}	E2	3530	≤ 17 e^2fm^4
5298	4^{+}	E2	4176	≤ 3 e^2fm^4
4116	3^{+}	E2	2995	≤ 12 e^2fm^4
3358	3^{+}	E2	2237	≤ 22 e^2fm^4
4398	4^{-}	E1	3277	$\leq 1.6 \times 10^{-2}$ e^2fm^2
6096	4^{-}	E1	4975	$\leq 4 \times 10^{-3}$ e^2fm^2

Photopeaks from the $^{18}F^{m}$ transitions, however, were not apparent in the Doppler-corrected γ-ray spectra accumulated during the $^{18}F^{m}$ runs. Due to the relatively poor resolution of the NaI array at these excitation energies, the limited statistics from the low rate of isomer beam on target, and high γ-ray background (due to in-flight decay), photopeaks from weak Coulomb excitation transitions were not observable above the high-energy γ-ray background. The upper-level limits for the experimentally-determined reduced transition strengths B(E1↑) and B(E2↑) of Coulomb excitations from the isomeric 5^{+} state to the states listed were then calculated using the intrinsic energy resolution of the γ array at the energies in question. (Suggestions for improving this type of measurement are discussed in Section 4.)

3.3. The In-Flight Decay of $^{18}F^{m}$ Nuclei

As noted, a large portion of the energy spectrum contains numerous events from photons assumed to be emitted during the in-flight decay of ^{18}F nuclei in the 5^+ isomeric state. The ^{18}F^{m} is de-populated through a two-step γ-ray cascade with energies of 184 keV and 937 keV (Fig. 1) emitted in rapid succession while moving at a significant fraction of the speed of light (0.27*c*). The emission of this γ-ray cascade can occur at any time after the production of the original excited state ^{18}F^{m} nucleus in the A1200 fragment separator (but with a half-life of 162 ns in the ^{18}F^{m} frame of reference). Moreover, these in-flight decay events happen at random times, making the exact location of the γ-ray emission impossible to specify. This eliminates the ability of our Doppler-correction to accurately arrive at the original energy of the emitted photons. This ambiguity in terms of the photon energy leads to a broad spatial distribution of events due to the isomeric de-excitation rays in the collected energy spectrum. This deficiency in our experiment is not fatal due to the de-excitation energies of the most probable collective levels built above the ^{18}F isomer being well above this masked energy region [i.e. in an energy region with a very low γ–ray background (see Table I)] and possible de-excitations occurring near the excitation target. Although the isomeric de-excitation γ-rays detected in the energy region from 500 to 1400 keV do mask possible low-energy ^{18}F^{m} Coulomb excitations, they also contain some interesting and unexpected information on the apparent in-flight decay of the isomeric state in the ^{18}F beam nuclei.

One can identify the number of decaying ^{18}F^{m} nuclei at various positions with respect to the physical position of the γ-array by segmenting the timing peak due to isomeric γ-rays detected in the NaI array. Careful analysis of the number of 184 keV-938 keV isomeric γ-ray cascades detected which were apparently emitted in the vicinity of the ^{197}Au excitation target is suggestive of an increased isomeric beam decay, possibly due to an interaction with the ^{197}Au target. One can deduce the number of expected ^{18}F^{m} isomeric γ-ray cascades occurring at the excitation target position by accurately knowing the position of the ^{197}Au excitation target with regards to the γ–array timing spectrum determined from timing spectra collected during the experiments described in [6].

The number of expected ^{18}F^{m} isomeric γ-ray cascades occurring in a timing segment representing decays emitted at the excitation target position detected by the NSCL large-angle array was calculated [6] and yields $N\gamma-\gamma$ = 2328 ± 48. When the calculated isomeric decay yield is compared to the measured number of ^{18}F^{m} isomeric γ-ray cascades accumulated for the timing segments corresponding to the length of the NSCL array (displayed in Figure 4), one finds on average good statistical agreement. The number of detected in-flight isomeric decays (identified by the detection of the characteristic 184 keV-937 keV γ-ray cascade) agrees within uncertainties ($\pm 1\sigma$) with the predicted value for a majority of the timing segments corresponding to areas within the array. A slight but statistically significant (up to 2σ) increase in the number of coincidences was observed at and following the timing segments corresponding to the position of the excitation target (as identified from the ^{197}Au Coulomb-excitation data [6]). One can eliminate the contribution of any ground-state E2↑ Coulomb excitations that populate the 937 keV ($J^{\pi} = 3^+$) excited state which would lead to an enhancement in the detection of the 937 keV γ-ray only by requiring the detection of both γ-rays emitted in the decay of a single isomeric nucleus.

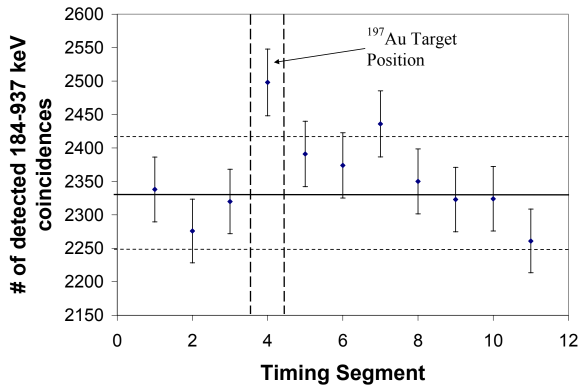

Fig. 4. Observed number of coincidences due to the in-flight decay of isomeric ^{18}F nuclei. Each timing segment corresponds to an 88 ps transit-time window. The position of the ^{197}Au target (denoted here by vertical dashed lines) was determined from ^{197}Au Coulomb-excitation data [6]. The horizontal lines represent the predicted value and the range of uncertainty ($\pm 2\sigma$) for the number of detected isomeric decays in a segment [note off-set scale].

The apparent increased decay rate at the ^{197}Au target position is generally greater than the contribution expected from ground-state Coulomb excitation to the isomeric state [*i.e.* double excitations from the 1^+ ground state (E2↑) to the 937 keV 3^+ level followed by excitation (E2↑) from the 3^+ level to the 5^+ isomeric state and the subsequent decays] as this is expected to be many orders of magnitude smaller than the observed enhancement. Also, once made in the isomeric state, the additional isomer "beam" nuclei would decay back to the 1^+ ground state with essentially a constant rate following the production target position. However we see the apparent enhanced isomer decay only near and slightly after the target. The decay rate at positions after the target implies a decay life-time of ≈160 ps and an isomeric decay rate enhanced by ≈ 7%. This also applies to reactions with non-^{18}F ions in the beam which eventually form ^{18}F^{m}, and hence are identified in the ^{18}F particle identification gate, unless these populate ^{18}F levels just below the 5^+ isomer (Fig. 1) to mimic the isomer γ-decays but with the $3^+ \rightarrow 1^+$ half life (*ca.* 50 ps). Obviously, in order to confirm the apparent enhanced isomer decay observed and determine the precise mechanism, further experiments with $^{18}F^{m}$ beams or similar isomeric nuclei will be needed, preferably with high-resolution HPGe detectors (see below).

4. CONCLUSIONS AND FUTURE WORK

We have studied intermediate-energy Doppler-corrected in-flight γ-decay following projectile excitation of $^{18}F_{g.s.}$ ($J^{\pi} = 1^{+}$) and $^{18}F^{m}$ ($J^{\pi} = 5^{+}$). The value deduced for B(E2↑) for the transition from the $^{18}F_{g.s.}$ ($J^{\pi} = 1^{+}$) to the 2523 keV ($J^{\pi} = 2^{+}$) excited state assuming Coulomb excitation is (5.5 ± 2.8) $e^{2}fm^{4}$. Upper limits on $^{18}F^{m}$ Coulomb excitation for several transitions to levels with known spins and lifetimes also have been determined.

A segmented HPGe large-angle γ-detector array with intrinsic energy resolution ca. two orders of magnitude better compared to NaI(Tl) has recently been installed at NSCL. While the detection efficiency of the new array is less than the efficiency of the current NaI(Tl) array, the large improvement in detector resolution should allow future in-flight measurements with $^{18}F^{m}$ and other isomer beams. Definitive measurements of the in-flight $^{18}F^{m}$ (and other isomer) Coulomb excitations together with studies of possible target-enhanced isomer decays thus appear feasible with a segmented HPGe arrays.

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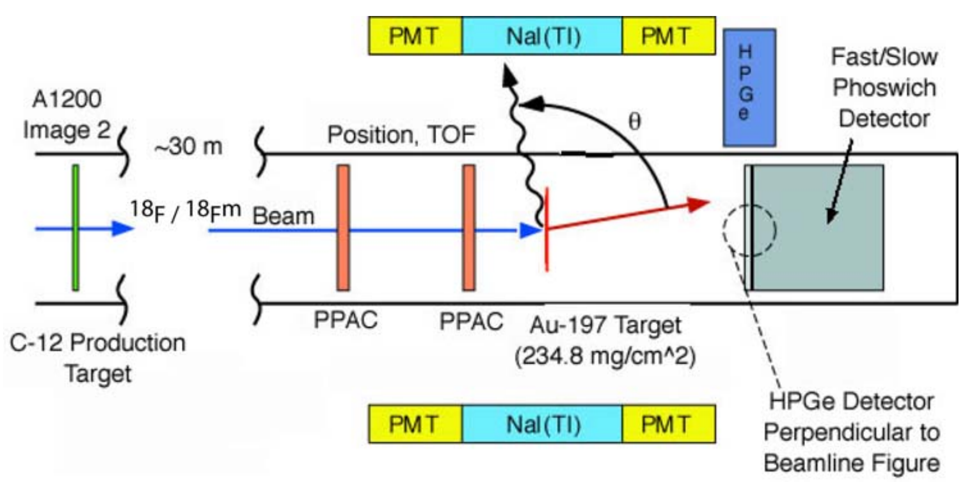

Fig. 2. A schematic of the experimental apparatus for particle detection, identification, and on-line secondary-beam purity monitoring during intermediate-energy Coulomb excitation.