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ON-LINE PROMPT AND DELAYED ELECTRON AND GAMMA RAY SPECTROSCOPY AT THE UNIVERSITY OF COLORADO CYCLOTRON LABORATORY*

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MASTER

The University of Colorado 132 cm FFAG cyclotron has several external beam facilities. One of these is presently intended for on-line measurements of γ ray and conversion electron spectra and is therefore simply referred to as the γ line. Beams of protons, deuterons, ^3He and α particles can be focussed onto the different target positions by a beam transport system using in total four quadrupole pairs and two 45° bending magnets (see Fig.1). Beam currents used during data acquisition varied from a few nA to 2 μA , depending upon the type of experiment being performed. Beam energies can be obtained up to 28 MeV for protons, 18 MeV for deuterons, 44 MeV for ^3He and 36 MeV for α particles. The fraction of the beam transmitted from the beam defining slits after the second bending magnet to the Faraday cup, with no target in place, was always greater than 80% and usually close to 100%. Thus the background produced without a target is very low. However, with targets of the order of 10 mg/cm^2 there is a significant amount of small-angle scattering of the beam. Due to the neutron background produced it was necessary to provide heavy shielding for the spectrometers. Therefore a concrete-block cave was built, with 61 cm thick walls and roof. With a beam current of 200 to 300 nA of 21 MeV protons on the target the neutron flux outside the cave is 400 neutrons/ cm^2 sec and in the cave at the γ detector position the neutron flux is 10 neutrons/ cm^2 sec. Inside the γ cave, additional shielding of lead and borated paraffin surrounds the detectors. Since it is not practical to put more shielding around the detectors, a time gating system has been developed to gate the data taking system on only during beam pulses.

Essentially only three different instruments have been employed to investigate the prompt and delayed radiation which result from the induced nuclear reactions; namely, lithium drifted germanium detectors, a two-meter curved crystal diffraction spectrometer, and a broad-range electron transport solenoid-Si(Li) spectrometer. This unique instrumental set-up

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on this γ line is a powerful tool for investigating rather complex spectra, as the instruments provide for high resolution electron and gamma ray spectroscopy, and allow assignment of multipolarities to the transitions observed. By means of coincidences and angular distribution measurements one can determine the order in which the transitions occur and the spin and parity sequences of the levels connected by these transitions. An additional advantage of nuclear structure studies with accelerators, which is not generally available in radioactive decay studies, is that one can measure γ ray branching ratios as a function of bombarding energy. If the γ rays deexcite a common level then the measured intensity ratios are independent of bombarding energy. This is a very good criterion to apply when assigning γ rays to nuclear levels. Furthermore the study of prompt γ ray and conversion electron spectra which result from nuclear reactions has another advantage above radioactive decay studies, in the fact that the reactions usually bring in several units of angular momentum into the nucleus, making it possible to excite considerably more levels than in most radioactive decays.

All the Ge(Li) detectors used in the course of the experiments were manufactured at the University of Colorado, Nuclear Physics Laboratory. The devices used are coaxially drifted and have volumes of approximately 15 cm^3 . The energy resolution of a detector which was used is 2.5 keV FWHM for the 1.33 MeV ^{60}Co photopeak. The equipment was calibrated for intensity with a standard set of absolutely calibrated γ -ray sources obtained from IAEA[†]. The prompt Ge(Li) γ -ray spectra are all recorded at a target-detector distance of approximately 1.2 m. The data are analyzed in the form of 1024 channel spectra with a Nuclear Data ND 160 pulse height analyzer. The recorded data are stored on magnetic tape and taken to the University of Colorado Computing Center for analysis.

Studies have been made of prompt and delayed gamma ray spectra resulting from reactions induced by beams of 7.5, 12, 16 and 26 MeV protons and 21, 30, 37.7 and 43 MeV ^3He particles incident on natural tantalum foils ($10\text{-}15 \text{ mg/cm}^2$). In fig. 2 the prompt γ -ray spectra from 26 and 16 MeV protons incident on tantalum are shown. The γ -ray spectra are rather complex and the analysis of the data from these spectra alone will be insufficient to uniquely establish the level scheme. All the prompt γ -ray spectra show prominent peaks at 596, 694 and 1040 keV as well as several weaker

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lines due to inelastic neutron scattering by ^{74}Ge , ^{72}Ge and ^{70}Ge in the detector itself.

The Ge(Li) detectors were also employed for angular distribution measurements of the prompt γ -ray spectra with respect to the incident beam direction. In these measurements a second Ge(Li) detector at a fixed angle of 90° was used as a beam monitor. The other Ge(Li) detector including the necessary and rather heavy lead and paraffin shielding was mounted on an air pallet (Clark Equipment Co.). This platform was lifted by an aircushion, making it easy to place the detector at the desired angle. The prompt γ -ray spectra were measured in the case of the $^{181}\text{Ta}(p, xn)$ reactions at angles of 60° , 90° , 120° , 150° and 166° for incident proton energies of 26, 16, 12 and 7.5 MeV. The target detector distance in all these measurements was one meter. The γ -ray spectra as a function of angle from 26 MeV protons on tantalum is shown in fig. 3. The study of the angular distributions of the different γ transitions emitted from the nuclei formed by the nuclear reaction permits assignment of multipolarities of the γ rays, and spins and parities of the levels involved. It has been found¹⁻⁴⁾ that a wide range of excited states populated in (particle, xn) reactions are well aligned so that γ rays exhibit angular distributions depending on multipolarities and the spin sequences. On the other hand if a γ ray, which is expected to exhibit an anisotropic angular distribution, in fact has an isotropic distribution, one expects this transition to be fed mainly via the excitation of an isomeric state.

The curved crystal spectrometer was used to perform accurate energy determinations of the prompt γ rays in the energy region 50-500 keV. The geometry of the spectrometer is of the DuMond type with a two meter focal length. The instrument is equipped with a bent germanium crystal using the $\langle 422 \rangle$ planes for diffraction. The thickness of the crystal is 1.6 mm. The full width at half maximum resolution of the spectrometer is given by $\Delta E_\gamma = 2.9 \times 10^{-5} E_\gamma^2$, where E_γ is in keV. Thus, ΔE_γ is 2.6 keV at 300 keV. A germanium crystal designed to use the $\langle 220 \rangle$ planes for diffraction is being tested and appears to have approximately twice the resolution of the $\langle 422 \rangle$ crystal. The spectrometer was calibrated in each run using the KX-rays of tantalum as a standard. All spectra are scanned at least twice, usually once on the left and once on the right diffracted peaks. The energy of the transitions are then obtained from $E_\gamma (\text{keV}) = \frac{\alpha}{T_L + T_R}$, where T_L and

T_R are the locations of the diffracted peaks. The value for the constant α is accurate to 2 parts in 10^5 . As an example of the data that have been taken, spectra from the $^{181}\text{Ta}(p,3n)^{179}\text{W}$ and $^{181}\text{Ta}(p,2n)^{180}\text{W}$ reactions are shown in fig. 4 and 5. The data are counted per integrated beam clock and recorded from the spectrometer in a Nuclear Data ND 181 FMR analyzer operating in the multi-scaler mode.

Prompt and delayed conversion electron spectra were studied with a broad-range electron transport solenoid equipped with a Si(Li) detector as an electron spectrometer. The details of the design of the instrument are given in the paper by Klank and Ristinen⁵⁾ presented at this meeting. The solenoid is also located in the γ cave on the external γ line. The target-detector distance of this instrument is 54 cm, and the Si(Li) detector is mounted with its face perpendicular to the axis of the solenoid, facing the target. The solid angle subtended by the electron detector for X- and γ -rays is very small (0.0017% of 4π ster), while the measured solid angle for electrons with a 64 mm^2 detector is 22%, 10% and 4% of 4π steradians at energies of 100, 600 and 1800 keV respectively, when the apparatus is operated at a magnetic field of 5500 gauss. The inside diameter of the free space for the electrons in the solenoid is 7.5 cm. Both the Si(Li) detector and the modified frontend of the preamplifier (Canberra 1408C) are cooled to liquid nitrogen temperature. The electron conversion spectrum of ^{137}Cs as recorded with a 4.7 mm thick, 9 mm diameter silicon detector is shown in fig. 6. The electron detector was operated at a bias voltage of -2400 volts and has a FWHM resolution of 3.0 keV for the 624 keV K-conversion electrons, although the count rate of the detector was around 6000 counts/sec. Very recently larger Si(Li) electron detectors (4 mm thick, 19 mm diameter) have also been tried in the solenoid. The preliminary results are very promising.

To investigate KX-e^- or $\gamma\text{-e}^-$ coincidences, a Si(Li) or Ge(Li) photon spectrometer can be mounted on the opposite side of the source with respect to the electron detector. As the K-conversion electrons are coincident with KX-rays produced as a result of the internal conversion process, KX-e^- coincidence measurements will be a useful tool in the interpretation of complex conversion electron spectra. For these measurements a Si(Li) photon detector (2.6 mm thick, 9 mm diameter) was used. Both the silicon detector and the modified front end of the preamplifier (Canberra 1408C) are cooled to liquid nitrogen temperature. The

target-detector distance is 1.5 cm to 2 cm and the photons are viewed through a 110 mg/cm^2 thick Be window plus a 0.25 mm thick mylar window. The detector had an energy resolution of 1.1 keV FWHM at γ -rays of 122.0 keV from a ^{57}Co source. A similar but thicker Si(Li) photon detector (10 mm thick, 9mm diameter) had an energy resolution of 1.4 keV FWHM at 122.0 keV.

The usefulness of the broad-range electron transport solenoid becomes quite evident from the electron transmission curves reported by Klank and Ristinen ⁵⁾. One may also point out that the actual source-size is not an important factor in the performance of the instrument. A weak low specific activity can thus be compensated for by using a large area source, if necessary up to a few cm^2 , and still allow for a thin source to avoid line broadening.

Some examples of investigations with the electron spectrometer device will be discussed below. At an early stage of the instrument before optimum performance was achieved a number of spectra were investigated. In fig. 7 and 8 the prompt conversion electron spectra are shown from the $^{159}\text{Tb}(p,2n)^{158}\text{Dy}$ and $^{169}\text{Tm}(p,2n)^{168}\text{Yb}$ reactions respectively. The spectra are obtained with 16 MeV protons on targets having approximate thicknesses of $700 \text{ } \mu\text{g/cm}^2$. The ^{158}Dy ground state rotational band transitions of 218 keV ($4^+ \rightarrow 2^+$), 321 keV ($6^+ \rightarrow 4^+$), 406 keV ($8^+ \rightarrow 6^+$) and 475 keV ($10^+ \rightarrow 8^+$) are observed as well as the transitions in the energy region of 677 to 998 keV. All are transitions from the γ band to the ground state band. In fig. 8 the ^{168}Yb ground state rotational band transitions of 199, 299, 385 and 455 keV are recognized together with the high energy transitions from the β and γ bands to the ground state band. The most striking features of this electron spectrum are the very strong 1197 and 1543 keV transitions observed earlier and assigned as E0 transitions by Graetzer et al. ⁶⁾. Our γ -ray data taken with a Ge(Li) detector show no presence of γ -rays at these energies, and thus confirm the E0 assignments for these transitions.

The prompt conversion electron spectra from 26 MeV and 16 MeV protons on a $300 \text{ } \mu\text{g/cm}^2$ thick tantalum foil are shown in fig. 9 and 10 respectively. These spectra together with the spectra shown in figures 2, 3, 4 and 5 comprise a large source of information on the levels excited in $^{179,180}\text{W}$. Preliminary analysis of these data reveals the rotational structure of several bands in ^{179}W including the ground state $[514]7/2^-$ band (energies in keV): g.s. ($7/2^-$), 119.94 ($9/2^-$), 264.67 ($11/2^-$), 432.15 ($13/2^-$) and 618.99 ($15/2^-$); the $[521]1/2^-$ band:

221.52 ($1/2^-$), 303.78 ($3/2^-$), 317.14 ($5/2^-$), 508.02 ($7/2^-$) and 532.05 ($9/2^-$); the [624] $9/2^+$ band: 308.97 ($9/2^+$) and 423.86 ($11/2^+$); the [512] $5/2^-$ band: 429.77 ($5/2^-$) and 530.11 ($7/2^-$); the [633] $7/2^+$ band: 477.46 ($7/2^+$) and 572.45 ($9/2^+$). Also a weak excitation of a possible three quasi-particle state at 719.77 keV consisting of the configuration $p[402]\uparrow p[514]\uparrow n[514]\downarrow$ coupling to $J^\pi=3/2^+$. The rotational members built upon this state are observed at 773.38 keV ($5/2^+$) and 849.18 keV ($7/2^+$).

The spectra concerning the $^{181}\text{Ta}(p,2n)^{180}\text{W}$ levels clearly show that, contrary to an earlier assignment⁶⁾, the 902 keV transition is not an E0 transition but rather an E1 + 9% M2 transition, in agreement with the results obtained by Goudsmit et al.⁷⁾ in the decay of ^{180}Re . As shown in fig. 11, which is only a part of the total disintegration scheme, the 902 keV γ transition deexcites the two-quasi particle state at 1006.0 keV, which consists of the two-proton state $[402]\uparrow [514]\uparrow$ coupling to $J^\pi=2^-$. The rotational levels built upon this state as deduced from the prompt γ -ray spectra are also included in fig 11. The 7.4 nsec half-life⁷⁾ of this state explains why the angular distribution of the 902 keV γ -ray is nearly isotropic. Furthermore, the angular distributions are isotropic for all the g.s. rotational members, indicating that the bulk of the feeding of this band is through the isomeric 5.2 msec state at 1528.8 keV. Of the more prominent γ -rays only the 454.6, 316.4, 225.0 and 196.5 keV transitions show a strong angular distribution, indicating that they do not result from a feeding through the isomers.

In the studies of the radioactive decay⁸⁾ of the 6.7 min ^{179}W activity the conversion electron spectrometer was used to establish a new 101.6 keV E4 transition in cascade with a 120.1 keV E2 γ -ray and competing with the 221.52 keV M3 isomeric decay to the ^{179}W ground state. The recorded electron spectrum shown in fig. 12 is the result of a bombardment of 26 MeV protons on a $300 \mu\text{g}/\text{cm}^2$ thick tantalum target. The spectrum is a sum of six successive activations, each measured for one half-life directly following the turning off of the proton beam. The disintegration scheme of $^{179\text{m}}\text{W}$ and ^{179}W is presented in fig. 13.

Finally, the electron transport solenoid has successfully been operated with the coincidence equipment for the study of the isomeric decay of $^{73\text{m}}\text{Se}$. The 25.9 keV E3 isomeric transition in $^{73\text{m}}\text{Se}$ has recently been observed by Murray et al.⁹⁾. From the beta decay^{9,10)} a spin-parity assignment was made of $J^\pi=1/2^-$ for

the 39 min. state. On the basis of the energy dependence of the cross-section for the $^{70}\text{Ge}(\alpha, n)^{73}\text{Se}$ reaction Akhmed et al.¹¹⁾, however, assigned $J^\pi=9/2^+$ to the 7.2h and $J^\pi=1/2^-$ to the 39 min. states in ^{73}Se . These authors also suggest that the 7.2h state is the isomeric one, however, these arguments are shown not to be valid by the above mentioned experiments^{9,10)}.

The partial half-life¹⁰⁾ for the isomeric transition is in agreement with an E3 multipole character. Therefore, this transition must end at a $7/2^+$ level, if a spin and parity of $1/2^-$ is assigned to the isomer. The preceding arguments suggest that either there is a $7/2^+ \rightarrow 9/2^+$ transition in cascade with the isomeric transition or the spin-parity assignment made by Akhmed et al.¹¹⁾ for the 7.2h ^{73}Se is incorrect.

The electron transport solenoid spectrometer with the coincidence equipment provides a unique facility for either confirming or rejecting the existence of a transition in cascade with the isomeric one. The latter transition will be almost completely converted and an M1(E2) transition would still have an appreciable γ decay component (e.g. about 10% of a 10 keV M1 transition in Se would still proceed by γ decay). Therefore, by gating on the L shell conversion electrons of the 25.9 keV isomeric transition and observing the entire low energy γ -ray spectrum above the LX-ray energies of about 1.5 keV one should be able to determine if there is a γ transition in coincidence with the isomeric transition. KX-rays should not be in coincidence with the L shell conversion electrons unless the cascade transition is K-converted. Therefore, this measurement will be conclusive even if the energy of the cascade transition is hidden in the Se and As KX-rays in a non-coincidence experiment. The experiments are described in more detail in ref.¹²⁾ and show that there is no transition in cascade with the 25.9 keV isomeric transition.

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Figure Captions

- Fig. 1 University of Colorado, Nuclear Physics Laboratory experimental facilities: Cyclotron and beam transport system. The broad-range electron transport solenoid-Si(Li) spectrometer is not shown on the figure, but is located near the curved crystal spectrometer.
- Fig. 2 Prompt gamma ray spectra as recorded with a Ge(Li) detector. The spectra resulted from a bombardment of 26 MeV and 16 MeV protons on a tantalum foil (10 mg/cm^2).
- Fig. 3 The gamma ray spectrum from 26 MeV protons on tantalum recorded at different angles with respect to the incident beam. The spectra from top to bottom were taken at 60° , 90° , 120° , 150° , and 166° respectively. The detector was a 15 cm^3 Ge(Li) spectrometer.
- Fig. 4 Prompt gamma ray spectrum as recorded with the two-meter bent germanium crystal diffraction spectrometer. The reaction was induced with 26 MeV protons on tantalum.
- Fig. 5 Prompt gamma ray spectrum from the $^{181}\text{Ta}(p,2n)^{180}\text{W}$ reaction using 16 MeV proton energy. The data are taken with the two-meter bent germanium crystal diffraction spectrometer.
- Fig. 6 The conversion electron spectrum of ^{137}Cs , as recorded with the broad-range electron transport solenoid-Si(Li) spectrometer. The spectrum was recorded with a countrate of about 6000 counts/sec.
- Fig. 7 Prompt conversion electron spectrum from the $^{159}\text{Tb}(p,2n)^{158}\text{Dy}$ reaction using 16 MeV protons.
- Fig. 8 Prompt conversion electron spectrum from the $^{169}\text{Tm}(p,2n)^{168}\text{Yb}$ reaction using 16 MeV protons.
- Fig. 9 Prompt conversion electron spectrum from the $^{181}\text{Ta}(p,3n)^{179}\text{W}$ reaction using 26 MeV protons.
- Fig. 10 Prompt conversion electron spectrum from the $^{181}\text{Ta}(p,2n)^{180}\text{W}$ reaction using 16 MeV protons.
- Fig. 11 Part of the total disintegration scheme of levels excited in ^{180}W by the $^{181}\text{Ta}(p,2n)^{180}\text{W}$ reaction.
- Fig. 12 The conversion electron spectrum of the 6.7 min. $^{179\text{m}}\text{W}$ decay.
- Fig. 13 Decay scheme of $^{179\text{m}}\text{W}$ and ^{179}W as reported in ref. 8).

Fig. 1

Fig.2

Fig.3

Fig. 4

5. 31. 5

TRANSPORT SOLENOID - Si(Li) DETECTOR
 ^{137}Cs CONVERSION ELECTRON SPECTRUM ($E_\gamma = 661.59 \text{ keV}$)
DETECTOR BIAS = 2000 VOLTS
DETECTOR THICKNESS = $4700 \mu\text{m}$

COUNTS/CHANNEL

K (624.15 keV)

2.98 keV FWHM

L (655.88 keV)

M

CHANNEL NUMBER

Fig. 6

Fig. 7

Fig. 8

4-10-69 RUN 5 16 MEV P ON TM169 0-15MEV 1/2 IN BAFFLE NORMAL POS

Fig. 9

Fig. 10

4-10-69 RUN 2 16 MEV P ON TA181 0-1 MEV 1/2 IN BAFFLE. NORMAL POS.

Fig. 11

Fig. 12

Fig.13