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the MIT Cockcroft-Walton Accelerator**

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Abstract

As part of our fusion product-diagnostic development program, we have begun a series of experiments with 14 MeV neutrons generated in a Cockcroft-Walton accelerator. Two different detectors have been used to measure the neutron yield: a silicon SBD and a Cu foil. The energy of the emitted neutrons has been determined by using two spectrometers: the SBD and a ^3He proportional counter. The reaction rate is monitored, with about $\pm 5\%$ accuracy, by detecting the α particles from $\text{D} + \text{T} \rightarrow \text{n} + \alpha$. The neutron yields obtained from the Si detector and the Cu activation had associated uncertainties of about $\pm 15\%$ and agreed well with the predicted values from α measurements.

I. INTRODUCTION

Neutron measurements have traditionally provided most of the data on fusion reactivity in experimental fusion plasmas.¹ The intensity of 14 MeV neutrons from D-T reactions gives information on the ion temperature and/or the tritium density. Neutron spectroscopy can give information about the ion distribution function.² For these reasons, we are developing 14 MeV neutron diagnostic systems using D-T reactions in a Cockcroft-Walton accelerator.

Tritium-burning fusion experiments generate copious 14 MeV neutrons.³ Experiments with only D fuel also produce them in the burnup of D-D generated tritons.^{4,5} A small percentage of confined tritons from D(D,p)T reactions in a tokamak will undergo D(T,n) α reactions after slowing down from 1 MeV to about 150 keV. One purpose of our D-T experiments is the study and characterization of 14 MeV neutron detectors to be used as tritium burnup monitors in tokamaks.

We are using a Cockcroft-Walton accelerator as a well-calibrated 14 MeV neutron source.⁶ The accelerator is operated at 150 kV, with a deuterium beam, to produce D-T reactions in a water-cooled ErT_{1.92} target. The ion source consists of a deuterium plasma generated by a 60 MHz R-F oscillator; ions are extracted through a variable potential. The beam consists of varying fractions of monatomic and molecular ions, depending on the condition of the ion source. We estimate that the beams used for this work consisted of \lesssim 20% molecular species. These ions are focused towards the accelerating section where 150 kV is distributed among ten electrodes. Once the beam reaches the drift tube, it goes through a positively biased collimator that reduces its size at the target to about 1 cm². Beam current is measured at the target, which is biased at 200 V to attract beam-generated secondary electrons. The reaction rate is

accurately determined (to within about 10%) through the detection of the α particles using a Surface Barrier Detector in vacuum (VSBD).

We present in this paper the results obtained during an initial tritium operation of the accelerator. In general, we attempt to utilize both active and passive detection systems simultaneously, so that we can compare their responses under the same conditions. Section II describes the experimental set-up when using Cu activation,⁷ two different SBD's, and a ^3He proportional counter. The results from these measurements are presented in Section III. We discuss the conclusions and future experiments in Section IV.

II. EXPERIMENTAL SET-UP AND MEASUREMENTS

A 3- μm thick fully loaded $\text{ErT}_{1.92}$ target and a Cockcroft-Walton accelerator⁸ operated at 150 kV have been used to produce a maximum of about 5×10^7 D-T reactions per second when the current measured at the target was 1.3 μA . At this low beam intensity, a water circulating system was considered enough to refrigerate the target without having contamination problems.

By counting the α particles in vacuum we measure the $\text{T}(\text{D},\text{n})\alpha$ reaction rate. For the 14 MeV neutron diagnostic we have tested three different methods: Cu activation, SBD's, and a ^3He proportional counter. An advantage of the activation technique is that, being a passive method, it is immune to electronic noise.⁹ In particular, the $^{63}\text{Cu}(\text{n},2\text{n})^{62}\text{Cu}$ reaction offers some attractive characteristics, such as high energy threshold (11 MeV), large and well known cross section, and high γ emission probability. One limitation of this technique is that it cannot provide time resolved measurements but only total neutron yield. On the other hand, active methods offer the possibility of time resolution, but electronic noise can, sometimes, be a serious problem.

Reaction rate monitoring

The reaction rate has always been measured with the associated particle technique,¹⁰ i.e. by detecting the α particles from $\text{D} + \text{T} \rightarrow \text{n} + \alpha$ using an SBD in vacuum (VSBD). The VSBD was placed at 29.4 cm from the target and 120° from the beam direction (see Figure 1). It was covered with a 0.5- μm mylar foil in order to stop the backscattered deuterons and a stainless steel collimator 0.51-cm in diameter was placed over the detector front.

Copper activation

Table I lists some of the relevant activation parameters for ^{63}Cu and other interesting elements that we are planning to use during future experiments.

We have chosen the $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ reaction for the first activation experiment, mainly, because it has a high detection efficiency and a well known cross section.¹¹ ^{62}Cu decays to ^{62}Ni by β^+ emission and about 39% of those positrons will be annihilated in the foil generating 0.511 MeV γ rays that we measure with a High Purity Germanium detector (HPGe). We have calculated the percentage of positrons absorbed inside the Cu using an exponential function that only depends on the foil thickness and the maximum energy of the β^+ emitter.¹²

The experimental configuration is illustrated in Figure 1. A natural Cu foil, 250 μm thick and 1.2 cm in diameter, was set at 90° from the beam direction and 4.8 cm from the center of the target. To infer the reaction rate from this measurement we did not include the effect of the scattered neutrons, although the high threshold of the reaction and the fact that the cross section decreases at lower energies will make this contribution smaller than about 20%.

Silicon detectors

While we used VSBD to measure α particles in vacuum, two different SBD's, outside the vacuum chamber, were used as active neutron detectors: a fully depleted SBD, 1500- μm thick and a partially depleted one with active thickness of 100 μm . We will henceforth refer to the fully depleted detector as FD and to the partially depleted one as PD.

Figure 1 shows the experimental set-up, that was the same for both SBD's. To reduce the neutron energy spread from the reaction kinematics, the fronts of the

detectors were placed parallel to the target instead of facing it (the SBD was rotated 90° with respect to its position in Fig. 1). The distance from the center of the SBD to the target was 5.4 cm and the angle from the beam direction 90°.

Neutrons entering the SBD are converted into charged particles inside the Si wafer through $^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$ and $^{28}\text{Si}(n,p)^{28}\text{Al}$ reactions.^{13,14} Again, the high thresholds of these reactions (3.5 MeV and 5 MeV respectively) constitute an advantage when discrimination against lower energy neutrons is necessary. This is a crucial consideration for choosing a detector suitable for low levels of 14 MeV D-T neutrons in a large flux of 2.5 MeV D-D neutrons.

^3He proportional counter

A ^3He spectrometer was also tested during this experiment. The gas pressure inside this cylindrical detector is about 3 atmospheres, its radius 5 cm and its length 60 cm. It was placed at 90° from the beam direction and 5 cm away from the target.

The most significant reactions that neutrons can undergo inside a ^3He detector are (n,p) and elastic scattering. At 14 MeV, the dominant detection process will be scattering, because it is about 7 times more probable than the capture reaction but also because it will be easier to stop the ^3He -recoils than the protons inside the detector.

III. RESULTS

From α particles measured in vacuum we have calculated $4.77 \pm 0.24 \times 10^7$ reactions per second when the deuterium beam current at the target was $1.2 \mu\text{A}$.

A typical α spectrum is presented in Fig. 2. Two peaks, one at 3.22 MeV and another at 3.10 MeV, indicate the presence of two beam components: a monatomic D^+ with full energy of 150 kV and a molecular D_2^+ where each deuteron has 75 kV.

Copper activation

We used the HPGe detector, previously calibrated in efficiency with a ^{226}Ra source, to collect the γ spectrum of Fig. 3a. The counting time began 155 seconds after the 3000-second irradiation of the Cu foil. For the sake of comparison, the γ background is shown in Fig. 3b.

The interference of $^{65}\text{Cu}(n,2n)^{64}\text{Cu}$ is small due to its relatively long half life (12.7 h) and low γ emission probability. We estimated this contribution to be 2.62 % and subtracted it from the γ spectrum.

We obtained a reaction rate of $4.71 \pm 0.73 \times 10^7$ when measuring at the same time $4.77 \pm 0.24 \times 10^7$ reactions per second from α particles in vacuum.

Silicon detectors

Two neutron spectra, taken with the fully depleted and the partially depleted SBD's, are shown in Fig. 4. Having calibrated the detectors with a ^{226}Ra source in vacuum, we could identify the α and proton peaks from different excited states of the ^{25}Mg and ^{28}Al nuclei.

Both spectra have a continuous background that could come from scattered neu-

trons and gamma rays generated outside the detector through (n,γ) reactions and activation of the stainless steel vacuum chamber. This background increases at lower energy. Below approximately 2.5 MeV (not shown in Fig. 4), contributions from different reactions taking place inside the detector (mainly elastic and inelastic scattering and β^- -decay of ^{28}Al nuclei) are added to the X and γ rays from outside.

The resolution at the α_o peak is about 180 keV, while a FWHM of only 55 keV is measured at the 7.5 MeV ^{226}Ra peak. Some factors contributing to this worsening of the resolution could be the neutron scattering taking place at the chamber, the presence of a molecular component of the beam, the target thickness and the partial deposition of energy by α particles born near the SBD edge.

When using the PD SBD (3 times thinner than the FD) we almost avoided the detection of protons from the $^{28}\text{Si}(n,p)^{28}\text{Mg}$ reaction because their range was larger than the Si thickness.

Using the cross section value of $13 \pm 2 \text{ mb}^{14}$ for the (n,α_o) reaction and taking the area under the α_o peak, we calculated a reaction rate of $4.04 \pm 0.7 \times 10^7$ when measuring at the same time $4 \pm 0.3 \times 10^7$ reactions per second from α 's in vacuum. To calculate the sensitivity of the SBD's to 14 MeV neutrons we have taken the active areas provided by the manufacturer, which are about a factor of two smaller than the Si-wafer areas.

With the PD SBD, and using the nominal depletion depth of $100 \mu\text{m}$, we obtained a rate about 50% higher than what we expected. If we include the total thickness of the detector ($530 \mu\text{m}$) in the sensitive volume, the rate would be almost four times smaller than what is measured with the VSBD detector.

^3He proportional counter

The neutron spectrum taken with the ^3He P.C. is shown in Fig 5. The presence

of some pile-up is evident if we look at the two peaks appearing at 0.96 MeV (wall effect edge + epithermal peak) and 1.52 MeV (twice the energy of the epithermal). We can avoid it by simply covering the detector with a cadmium shield, as we have done before for the 2.5 MeV neutron measurements⁶. The spectrum was calibrated with the epithermal peak (764 keV) and the first edge from the wall effect (191 keV). The detector pressure is too low to stop the 10 MeV protons from ${}^3\text{He}(n,p){}^3\text{H}$, but we can clearly see the recoil edge from ${}^3\text{He}(n,n'){}^3\text{He}$.

IV. CONCLUSIONS AND FUTURE WORK

We have used a Cockcroft-Walton accelerator as a well calibrated 14 MeV neutron source to study the response of several neutron detectors. Their behaviour under irradiation of 2.5 MeV neutrons can also be studied with the same accelerator.

We have found a good agreement between α and neutron rates from D-T when using, for the latter, a fully depleted SBD or Cu activation. However, the uncertainties associated with the neutron measurements are higher than 30%.

Some of the future improvements on our development of 14 MeV neutron diagnostics include the utilization of the standard Monte Carlo neutron transport code (MCNP) in order to take into account the effects of neutron scattering in the experimental environment. Concerning the activation technique, we are planning to expose a thick Cu piece, instead of a foil, to 14 MeV neutrons and compare the achievable accuracy in both cases. We will also test other elements with different threshold energies. Some improvements concerning the SBD's as 14 MeV neutron detectors include the setting of a low level discriminator around 7 MeV to avoid the detection of γ rays. An effort will be made on trying to better understand the response of partially depleted SBD's to 14 MeV neutrons. Other silicon detectors, such as ion implanted ones, will also be considered as possible candidates for neutron detection. The modeling of a Si detector response will be studied to try to unfold the original energy spectrum. It will be particularly useful when the spread in neutron energies will be larger than the detector resolution. We will also study the minimum conditions on a deuterium plasma for the applicability of these detectors to tritium burnup measurements with reasonable time resolution.^{14,15}

We will also try to exploit the response of the ^3He proportional counter to 14 MeV

neutrons through their elastic scattering with the ^3He nuclei. An integration of the continuous spectrum from, at least, 3 MeV will be necessary in order to discriminate against D-D neutrons.

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¹⁶ O. N. Jarvis, JET-P(93)30.

FIGURE CAPTIONS

Table I. 14 MeV neutron activation reactions in different elements.

Fig. 1. Experimental configuration diagram of the detectors' setting around the chamber. VSBD, in vacuum, measures α particles. The 14 MeV neutron detectors - SBD and Cu foil- are outside the target chamber. To reduce the neutron energy spread from the reaction kinematics, the front of the SBD was placed parallel to the target instead of facing it (it was rotated 90° in relation to the position shown in the figure).

Fig. 2. D-T α particle spectrum from an SBD placed at 120° from beam direction. Two peaks, one at 3.22 MeV and another at 3.10 MeV, indicate the presence of two beam components: a monatomic D^+ with full energy of 150 kV and a molecular D_2^+ where each deuteron has 75 kV.

Fig. 3. γ -ray spectra, around 0.511 MeV, taken with a HP-Ge detector. a) From Cu activation. b) Background.

Fig. 4. 14 MeV neutron spectrum from $^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$ and $^{28}\text{Si}(n,p)^{28}\text{Al}$ reactions inside a silicon detector. The different peaks correspond to the ground and excited states of the residual nuclei. a) Fully depleted SBD 1500- μm thick. b) Partially depleted SBD with nominal active thickness of 100 μm .

Fig. 5. Neutron spectrum from a ^3He proportional counter. a) Wall effect, b) epithermal peak, c) double-peaked structure from pile-up, d) ^3He -recoil distribution.

Table I.

Element	Reaction	Threshold (MeV)	σ^{14MeV} (mb)	Half-life	E_γ (MeV)
Cu	$^{63}\text{Cu}(n,2n)^{62}\text{Cu}$	10.9	480	9.73 m	0.511
Ti	$^{46}\text{Ti}(n,2n)^{47}\text{Ti}$	13.2	280	3.09 h	0.511
Ni	$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	13	250	36 h	1.37
Zr	$^{90}\text{Zr}(n,2n)^{89}\text{Zr}$	13	610	4.18 m	0.588
In	$^{115}\text{In}(n,2n)^{114m}\text{In}$	9	1300	50 d	0.19

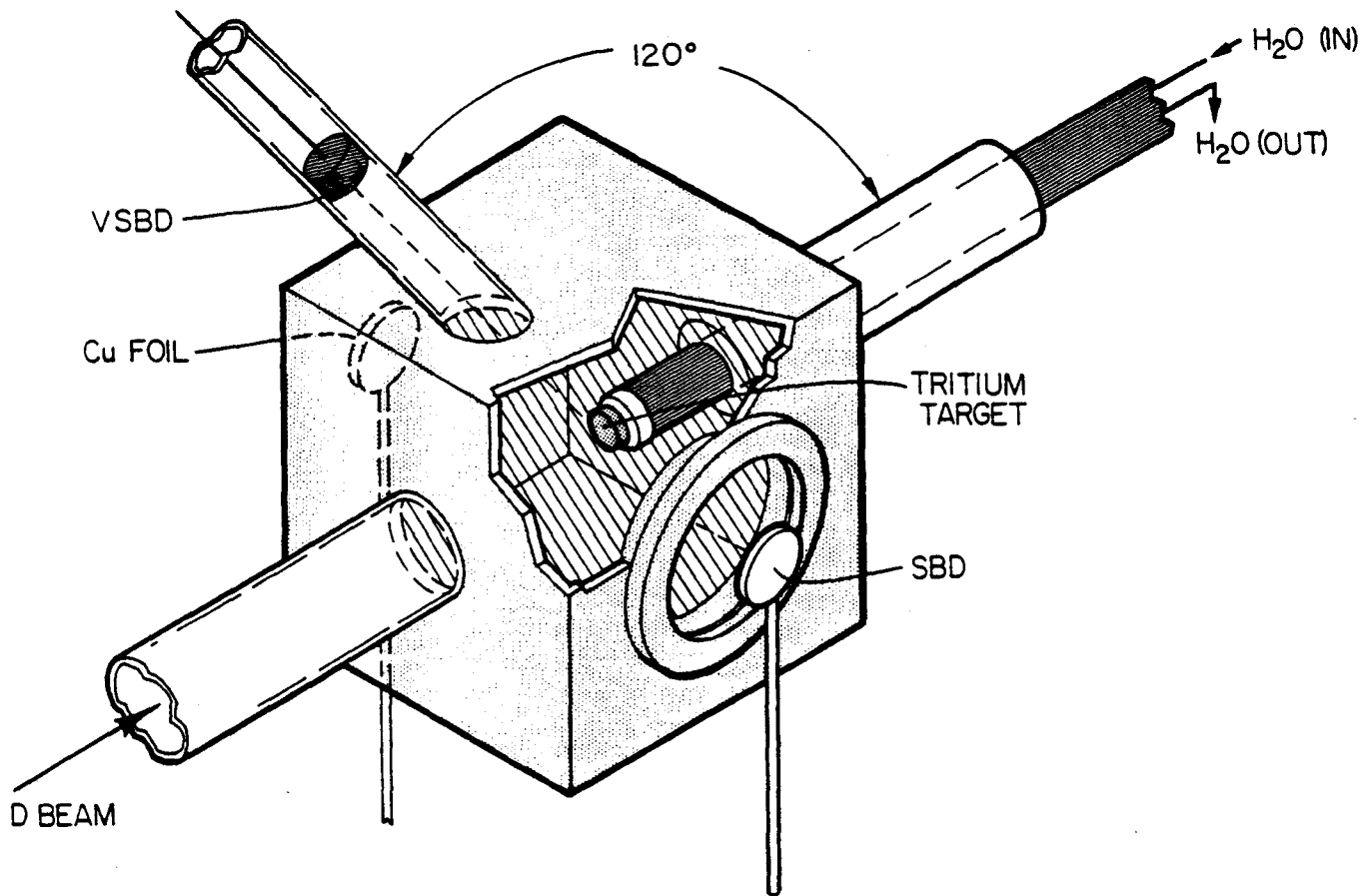


Fig. 1.

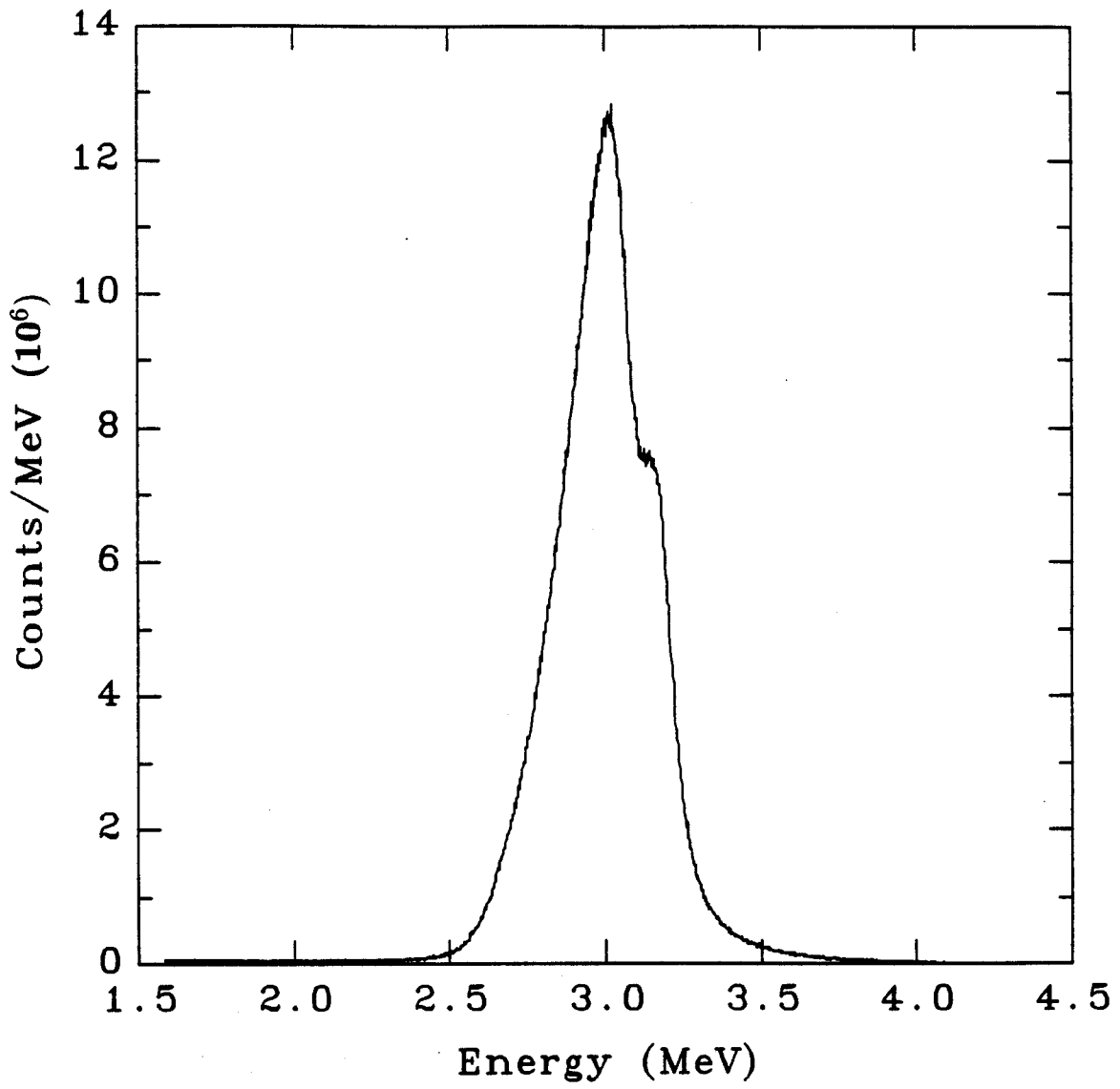


Fig. 2.

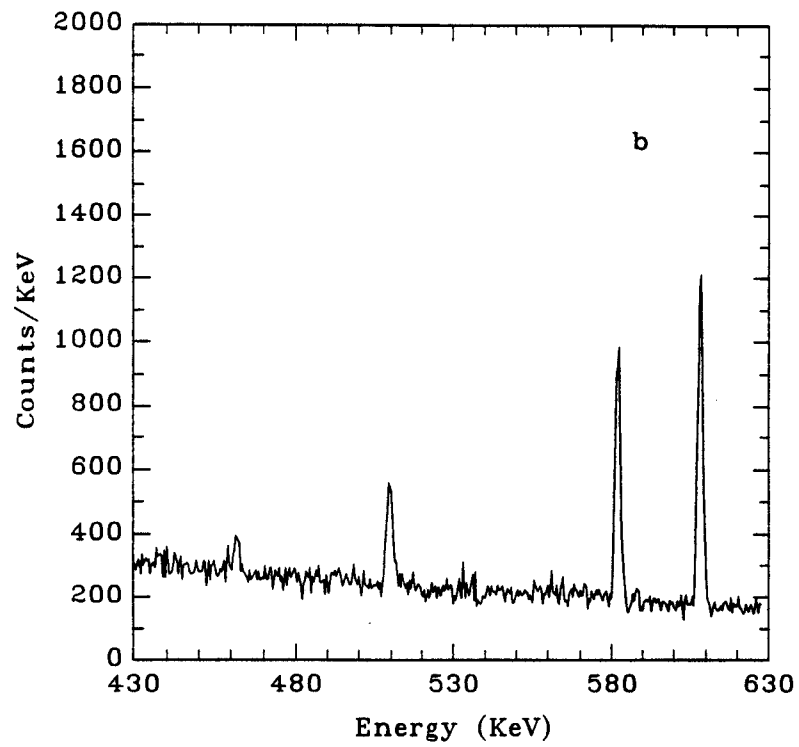
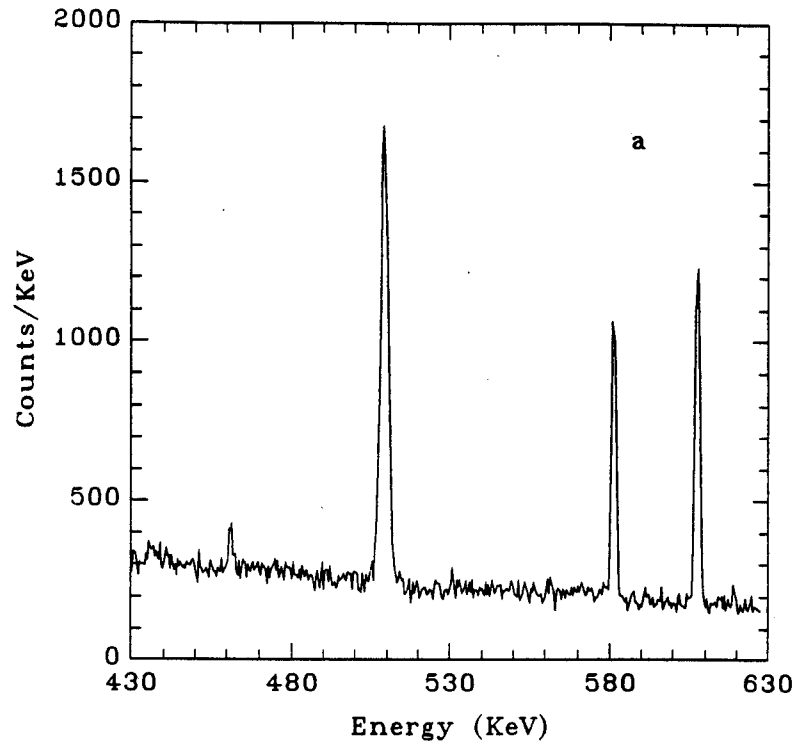


Fig. 3.

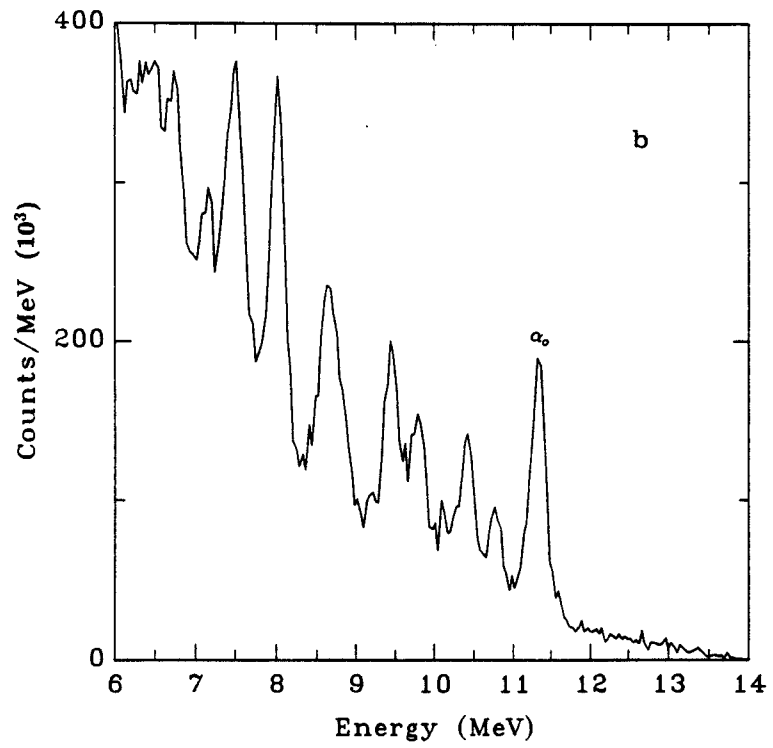
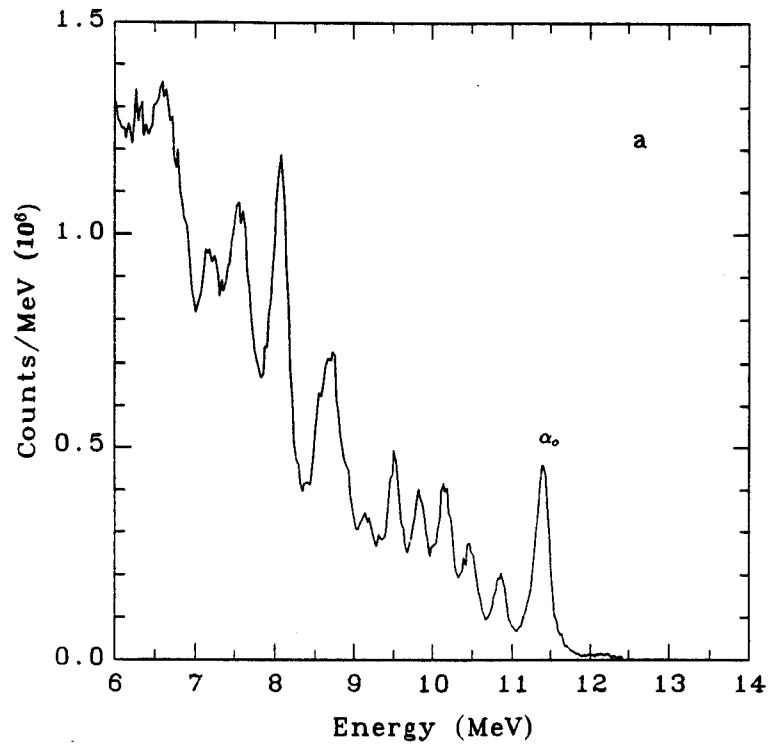


Fig. 4.

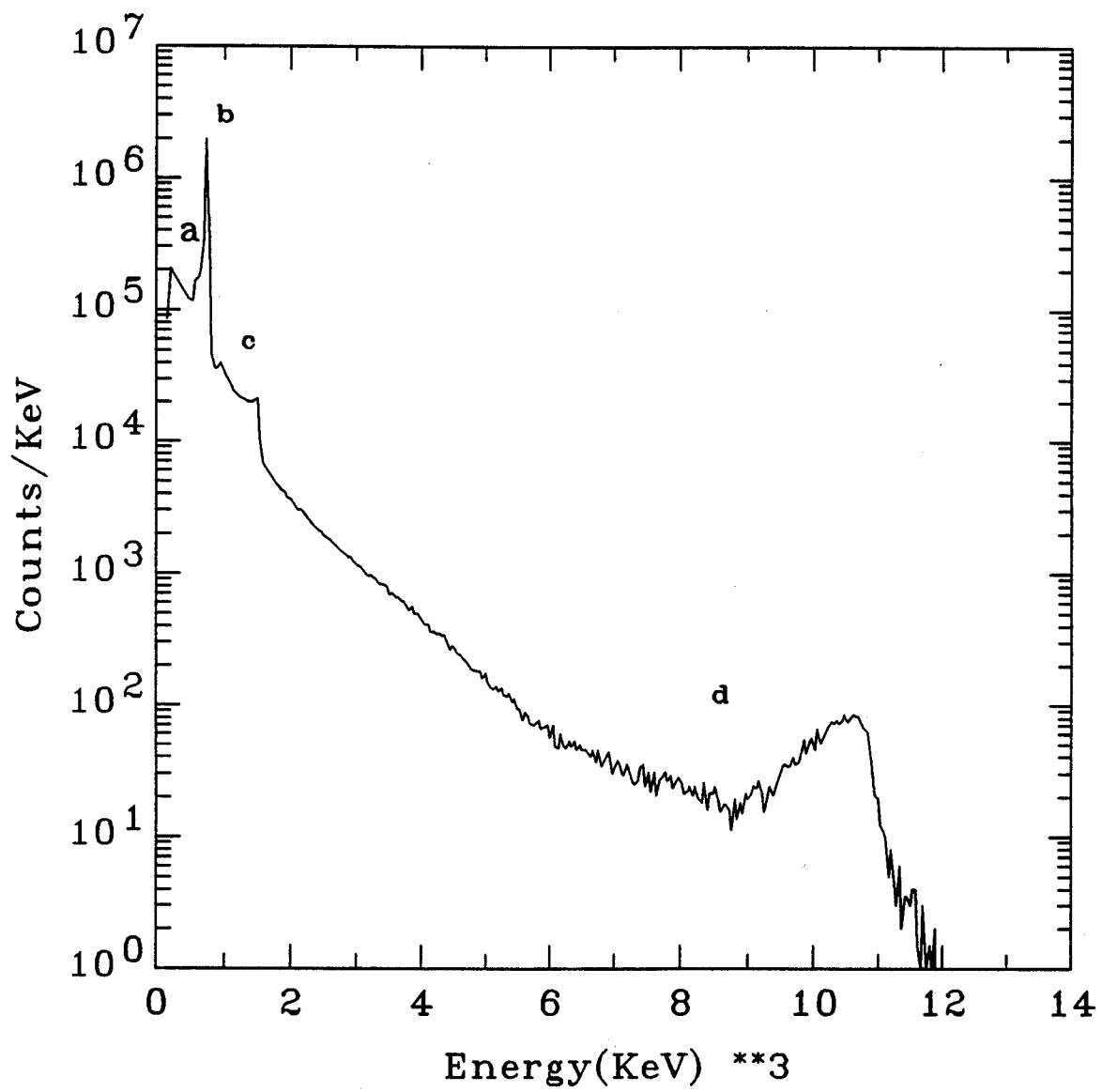


Fig. 5.