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July 1983

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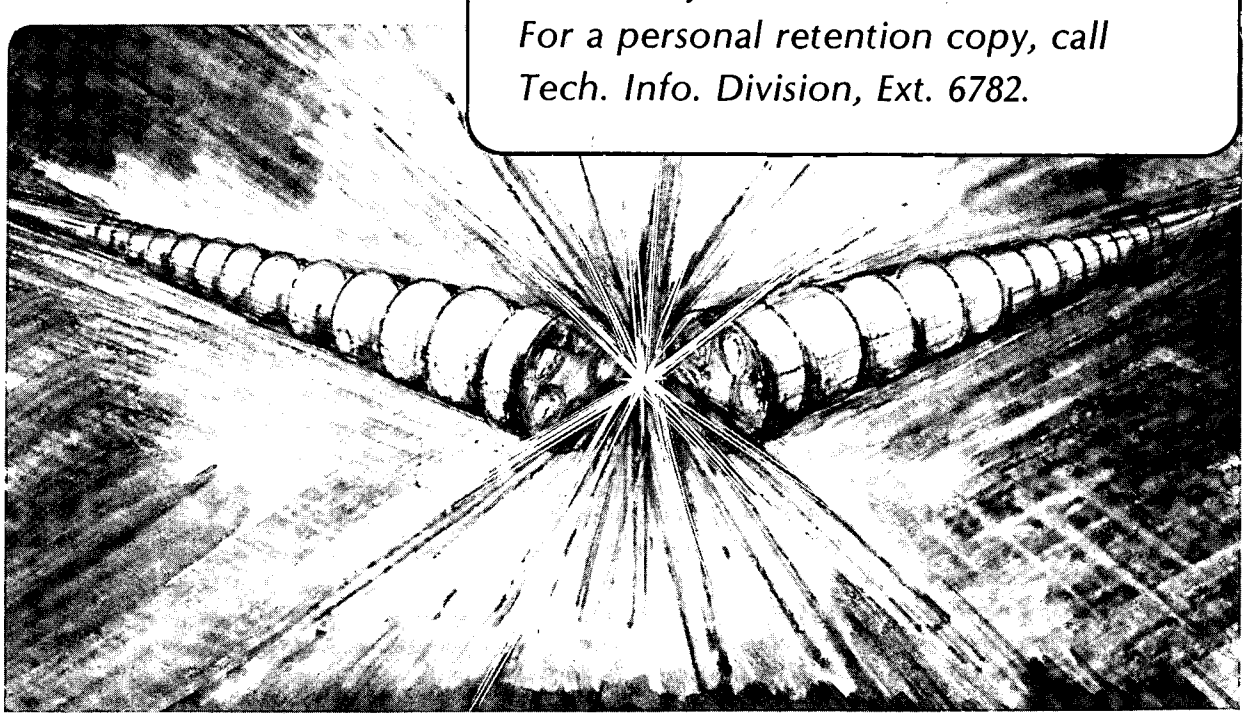

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Deuterium Beam Species Measurement by D-D Fusion Product Analysis*

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ABSTRACT

Results are discussed for a diagnostic method of determining molecular composition of ions exiting an 80-kV high-power ion source designed for neutral-beam heating in controlled fusion research. By viewing the charged products of a d-d reaction from a deuterium beam in a deuterium gas target, one can calculate the proportion of full, half, and third energy products extracted from the accelerator.

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INTRODUCTION

The high-power neutral deuterium beams used to heat magnetically confined plasmas for controlled fusion research consist of an admixture of D^+, D_2^+, and D_3^+. In an earlier paper[1] Smith and Strathman described a technique for determining the molecular composition (species) of deuterium ions exiting a source.

The method entails using a surface barrier detector to view backward-emitted (135°) particles from the proton-trition branch of the d-d fusion reaction which occurs in the neutralizer. Since the D^+,D_2^+, and D_3^+ ions have the same energy when leaving the source, the energy per nucleon is in the ratio 1:1/2:1/3, respectively. The difference in the center-of-mass motion results in a difference in the observed energies for the three species.

In the present paper we report results for a higher-resolution,

larger-area detector then that described previously.[1] The measurements were made at the Lawrence Berkeley Laboratory, Neutral Beam Engineering Test Facility with a 40-A, 80-kV source. Our results will be compared with those from Doppler shift spectroscopy.

METHOD

A schematic of the experiment is given in Fig. 1. We view backward-emitted particles from the triton-proton branch of the d-d fusion reaction: $d+d \rightarrow t(1.01\ \text{MeV}) + p(3.02\ \text{MeV})$. If one observes at an angle θ, then the energy of the detected triton or proton is

$$E_{t,p} = AW(\cos\theta + \sqrt{C/A - \sin^2\theta})^2,$$

where $A = M_d M_{t,p}(E_{inc}/W)/D,$

$$C = M_d M_{p,t}(1+Q/W)/D,$$

$$D = 2M_d(M_t+M_p),$$

Q = Reaction energy = 4.03 MeV,

W = Total energy = $Q + E_{inc}$ (in Mev),

and t, p, and d refer to tritions, protons, and deuterons, respectively. E_{inc} is the incident deuteron projectile energy in the lab system.

For an 80 kV incident beam, and a detection angle of 135°, we obtain for the outgoing proton energies

E_{full} = 2806 keV; E_{half} = 2863 keV; E_{third} = 2890 keV;

full, half, and third refer to products from D^+, D_2^+, and D_3^+, respectively.

EXPERIMENT

The experimental geometry is shown in Fig 1. The main drawback to the original detection system[1] was the use of Cu foils (500μg/cm^2) to block light entering the detector. This resulted in scatter and energy

degradation of the beam. Instead of foils, we now have 240 $\mu g/cm^2$ of aluminum deposited onto the entrance surface of an Ortec 150 mm^2 ruggedized surface barrier detector. The gold barrier is on the opposite face, and the detector is biased negatively. The maximum crystal depletion depth is 300 μm. The relative difference in dE/dx for full, half, and third-energy tritons and protons passing through the Al is negligible. The energy loss for protons (2.8 MeV) is $\approx$0.8% and for tritons (780 keV) $\approx$10%, based on tables in Northcliffe and Schilling.[2]

The collimation is the same as that described in Ref. 1, i.e., a stack of stainless steel mesh 1.27 x 5.08 x 0.128 cm. The acceptance angle in the emission plane is $\pm 1.4^\circ$, and in the transverse plane is $\pm 14^\circ$ to allow viewing the complete beam width. The collimator was biased at +24V to keep electrons out of the detector, but the bias had no effect on the resolution. The detector was 76 cm from the beamline center, yielding a solid angle of 2×10^{-5} sr.

The preamplifier and detector were operated in vacuum. To cool the preamplifier we used a thermopile, and the resolution improved about 20% over the uncooled system.

RESULTS

Figure 2 shows a complete spectrum for an incident deuterium beam energy of 82 kV. The He^3 peaks (from $d+d \rightarrow He^3 + n$) are superimposed on a large background, presumably due to light emitted by the neutralizing gas. We did not attempt to find an analytical fit to this pronounced background, so the He^3 data were not analyzed. Figures 3(a) - 3(f) show triton and proton spectra at 82, 63, and 43 kV. These data were analyzed with a simultaneous fit of three Gaussians. The background was determined by choosing 10 channels at both the high and low energy ends of the spectrum. The counts were averaged and a slope determined from the two points. The slope was then held constant in the fitting routine, and the intercept was allowed to vary. For the Gaussians the positions and amplitudes were variable parameters in each

of the three peaks. The width (σ_w) also was a variable, but set at the same value for all 3 peaks. Therefore, the full energy part of the spectrum was the main factor determining the width of the Gaussian. There was no physical reason to expect σ_w to be different for the full, half, and third energy species, and, when the width for each peak was allowed to vary independently, the resulting width ratios were inconsistent for tritons and protons.

To obtain the relative fractions of ionic species, the three areas must be divided by the cross section and the multiplicity (1,2, or 3 for D^+, D_2^+, or D_3^+, respectively). The cross sections are taken from the NRL Plasma Formulary[3] which gives $\sigma(E)$ in analytical form. The uncertainty in the cross section is calculated from interpolations of the data in Ref. 3. For example, at 78.6 kV the error is ±7%; at 38.6 kV, ±8%; and between 24 and 29 kV, ±8%.

We must also apply a correction to the NRL value due to the asymmetry in the differential cross section. In the lab frame the observation angle is fixed at 135°. To evaluate $d\sigma/d\Omega|_{lab}$ we must solve for the center-of-mass emission angle of the detected particle. The function $d\sigma/d\Omega|_{cm}$ is slightly anisotropic, and, the lab distribution is very similar because the incident energy E_{inc} is much less than the reaction energy Q. (For more details see Ref. 4.)

In Table I we present the results for 43, 63, and 82 kV incident deuterium beams. We compare proton and triton species fractions and those obtained with Doppler shift spectroscopy (OMA).[5] Within the quoted error bars, the full and third energy fractions disagree for the d-d and OMA methods. However, the agreement improves with increase in incident beam energy. This might be attributed to better counting statistics. Consider the following: The computer determined a background, for the 82 kV tritons, of ≈62 counts at the third energy peak, 69 at the half energy peak, and 84 at the full energy peak.

If the background were 100 counts higher (and it is possible to justify this based on the poor fit to the background as seen between the full and 1/2 energy peaks) then the specie ratio is 80:14:7. This is in agreement with the OMA results. This "new" background has some physical basis in parasite beam (i.e., particles which charge exchange in the accelerator grids and are therefore neutralized before receiving full accelerator voltage). A similar background is seen with the high-resolution Doppler shift spectroscopy and is accounted for in the OMA fits.

For future experiments we plan to run the preamplifier in air, with only the detector in vacuum. This will facilitate shock mounting of the preamplifier which is microphonic. It may also eliminate the need for cooling with a thermopile.

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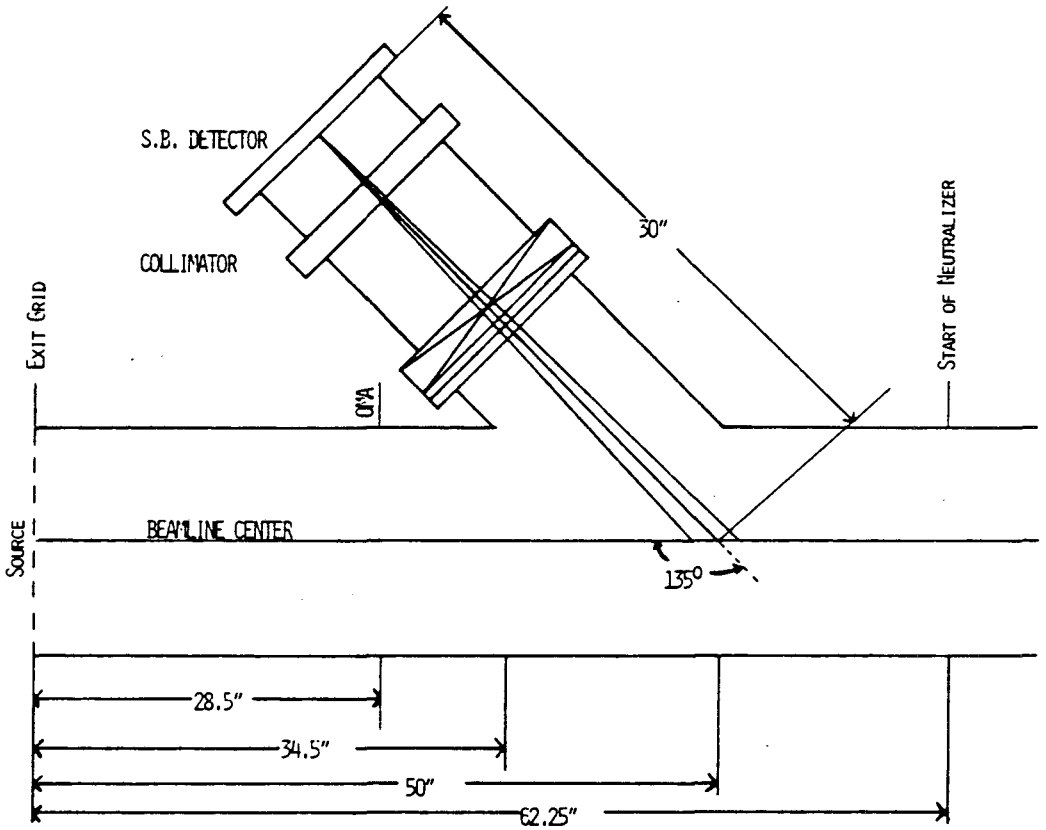
Fig. 1. Schematic drawing of the experiment. The accelerated D^+, D_2^+, and D_3^+ ions emerge from the exit grid on the left-hand side and travel toward the target area beyond the right-hand side of the drawing. The detector sees fusion reaction products emitted within a flattened fanlike region. The energy of the incident deuterons subtracts from the energy of the detected tritions or protons.

Fig. 2 Spectrum of fusion products (He^3, t, p) resulting from an 82-kV deuterium beam incident on a deuterium gas target.

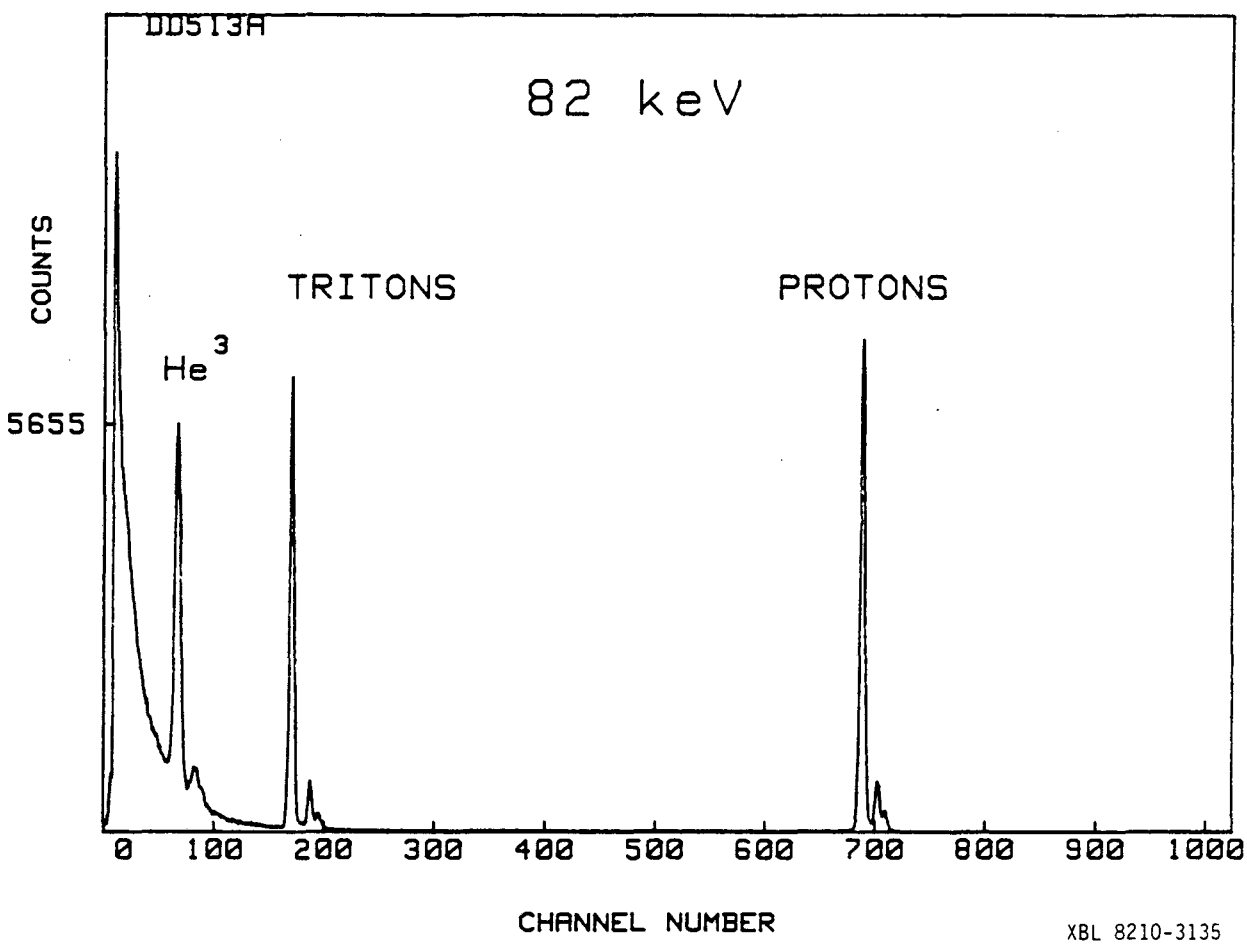
Fig. 3 Gaussian-fitted spectrum of full, half, and third energy fusion products from a deuterium beam incident on a deuterium gas target. a) incident beam energy: 82 kV, reaction product: tritions, beam time: 37 sec; b) incident beam energy: 82 kV, reaction product: protons, beam time: 37 sec; c) incident beam energy: 63 kV, reaction product: tritions, beam time: 8 sec; d) incident beam energy; 63 kV, reaction product: protons, beam time: 8 sec; c) incident beam energy: 42 kV, reaction product: tritions, beam time: 7.5 sec; f) incident beam energy: 42 kV, reaction product: protons, beam time: 7.5 sec.

Table I Relative specie fraction for trition and proton reaction products from D^+ (full), D_2^+ (half), and D_3^+ (third) incident beams at energies of 43, 63, and 82 kV on a deuterium gas target. Included in this table are the fractions obtained with Doppler shift spectroscopy (OMA).



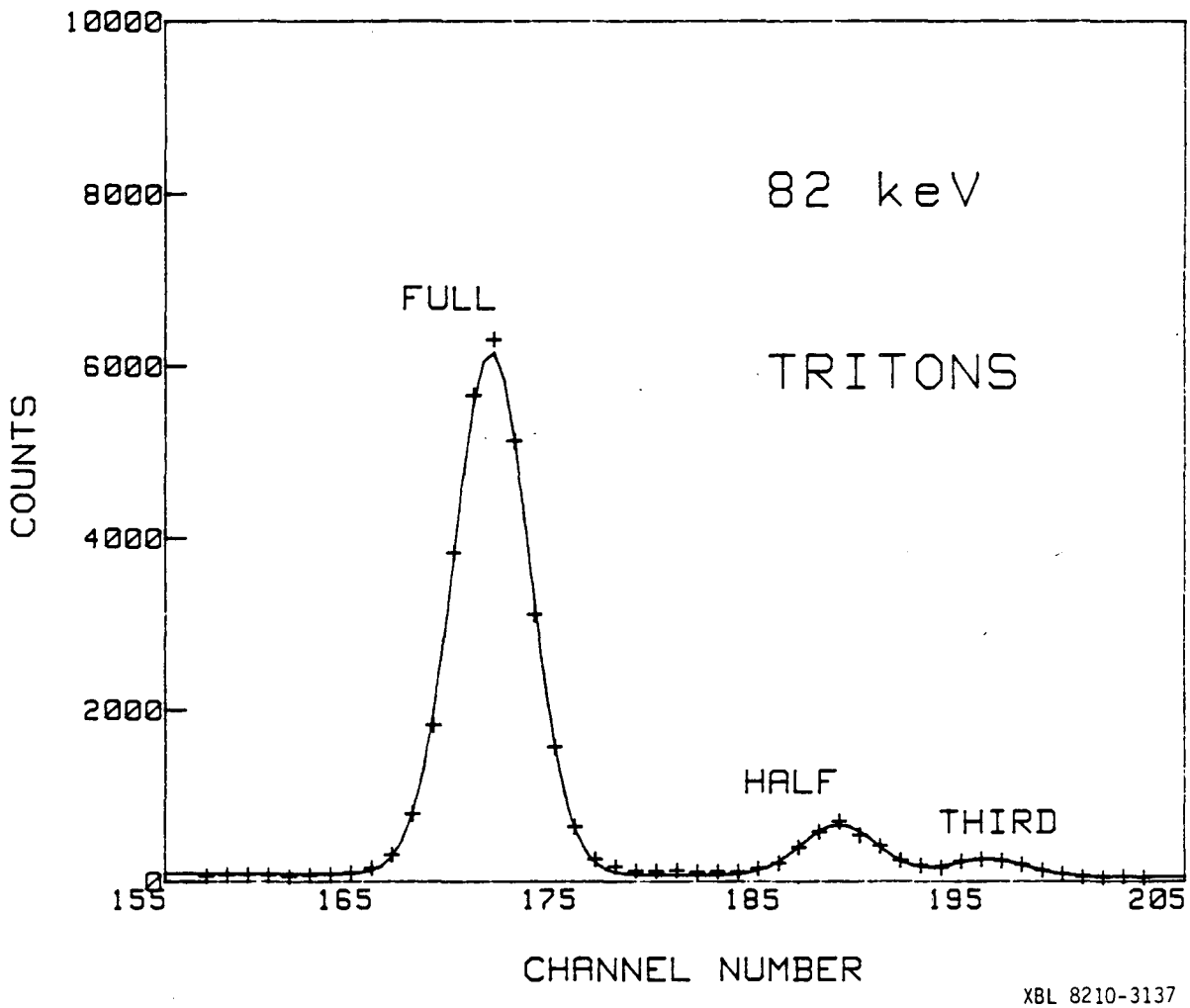
SCHEMATIC DRAWING OF THE EXPERIMENT. THE ACCELERATED D^+, D_2^+, AND D_3^+ IONS GO FROM THE EXIT GRID AT THE LEFT-HAND SIDE TOWARD A TARGET AREA BEYOND THE RIGHT-HAND SIDE OF THE DRAWING. THE DETECTOR SEES FUSION REACTION PRODUCTS EMITTED WITHIN A FLATTENED FANLIKE REGION. THE ENERGY OF THE INCIDENT DEUTERONS SUBTRACTS FROM THE ENERGY OF THE DETECTED TRITONS OR PROTONS.

Fig. 1



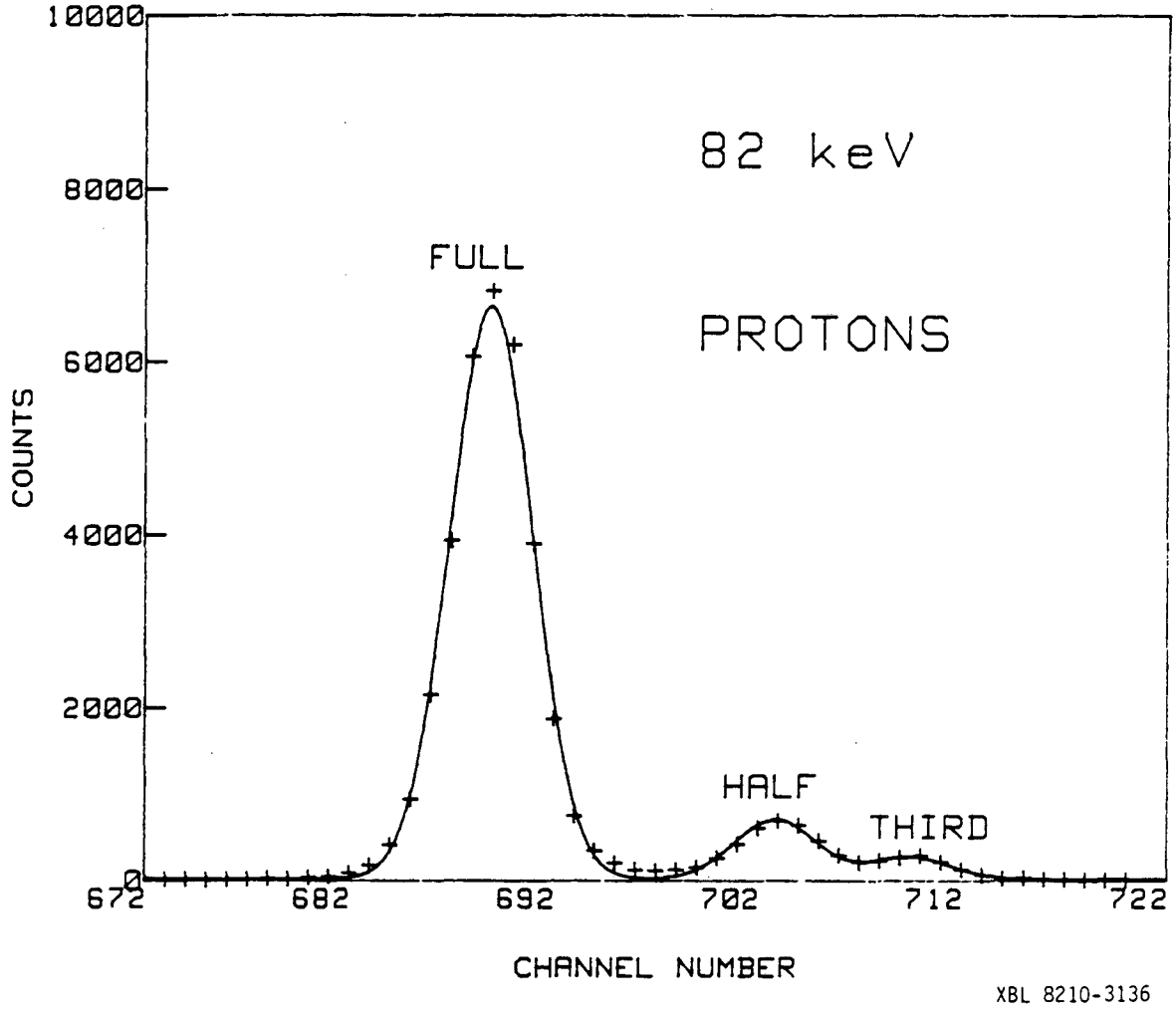
SPECTRUM OF FUSION PRODUCTS (He^3, T, P) RESULTING FROM AN 82-kV DEUTERIUM BEAM INCIDENT ON DEUTERIUM GAS IN A NEUTRALIZER.

Fig. 2



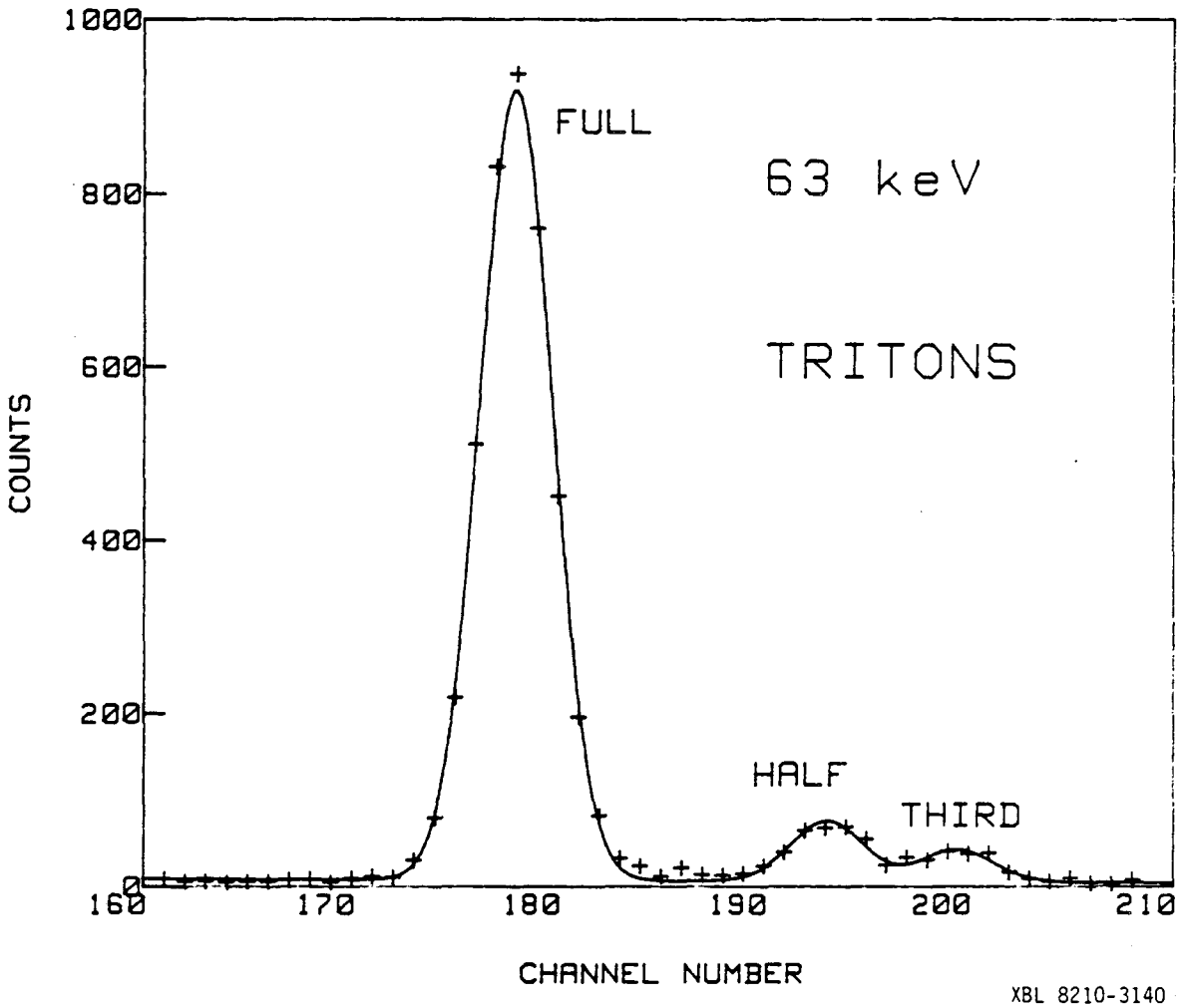
GAUSSIAN-FITTED SPECTRUM OF FULL, HALF, AND THIRD ENERGY FUSION TRITONS FROM AN 82-kV DEUTERIUM BEAM INCIDENT ON A DEUTERIUM GAS TARGET.

Fig. 3a



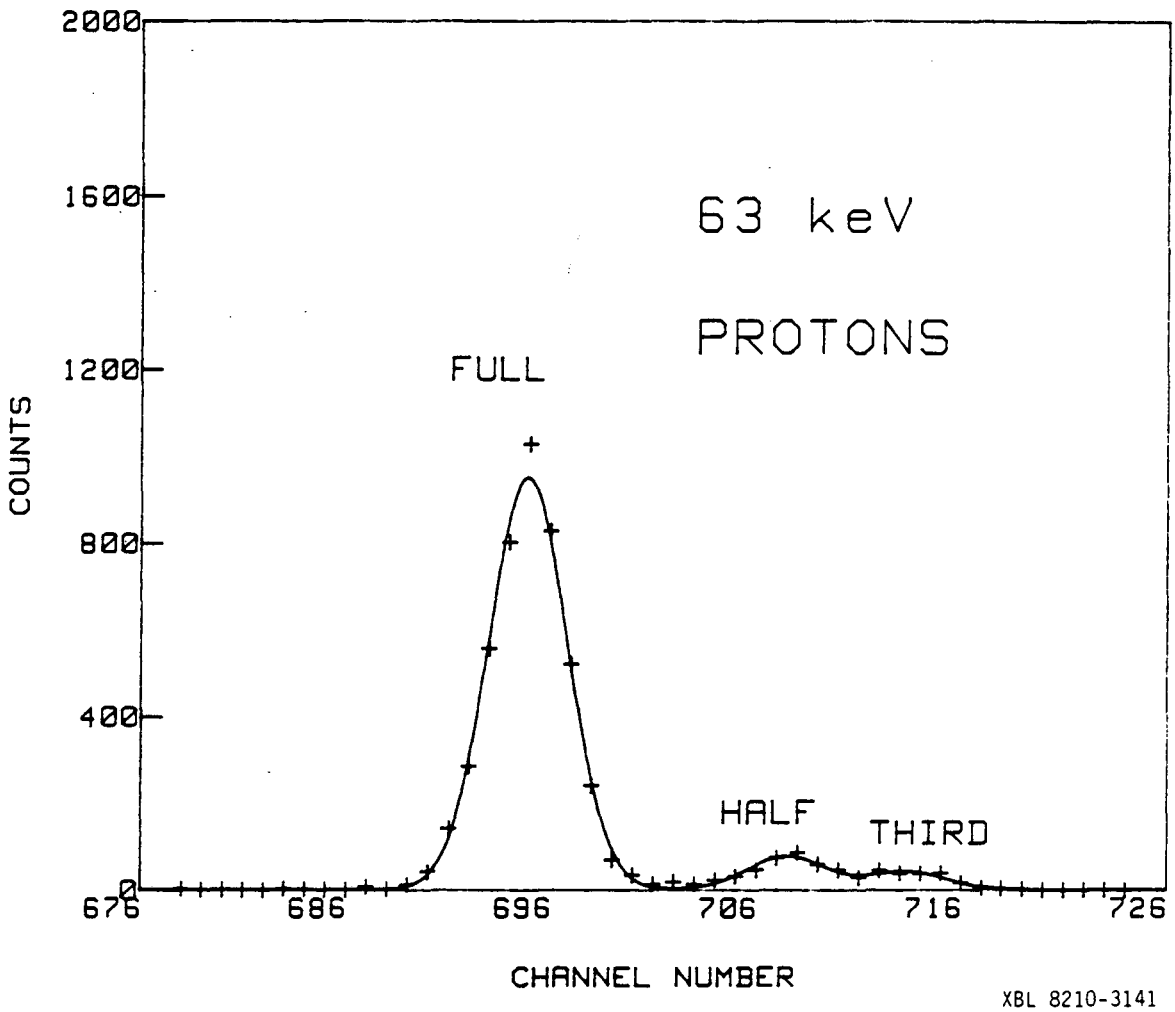
GAUSSIAN-FITTED SPECTRUM OF FULL, HALF, AND THIRD ENERGY FUSION PROTONS FROM AN 82-kV DEUTERIUM BEAM INCIDENT ON A DEUTERIUM GAS TARGET.

Fig. 3b



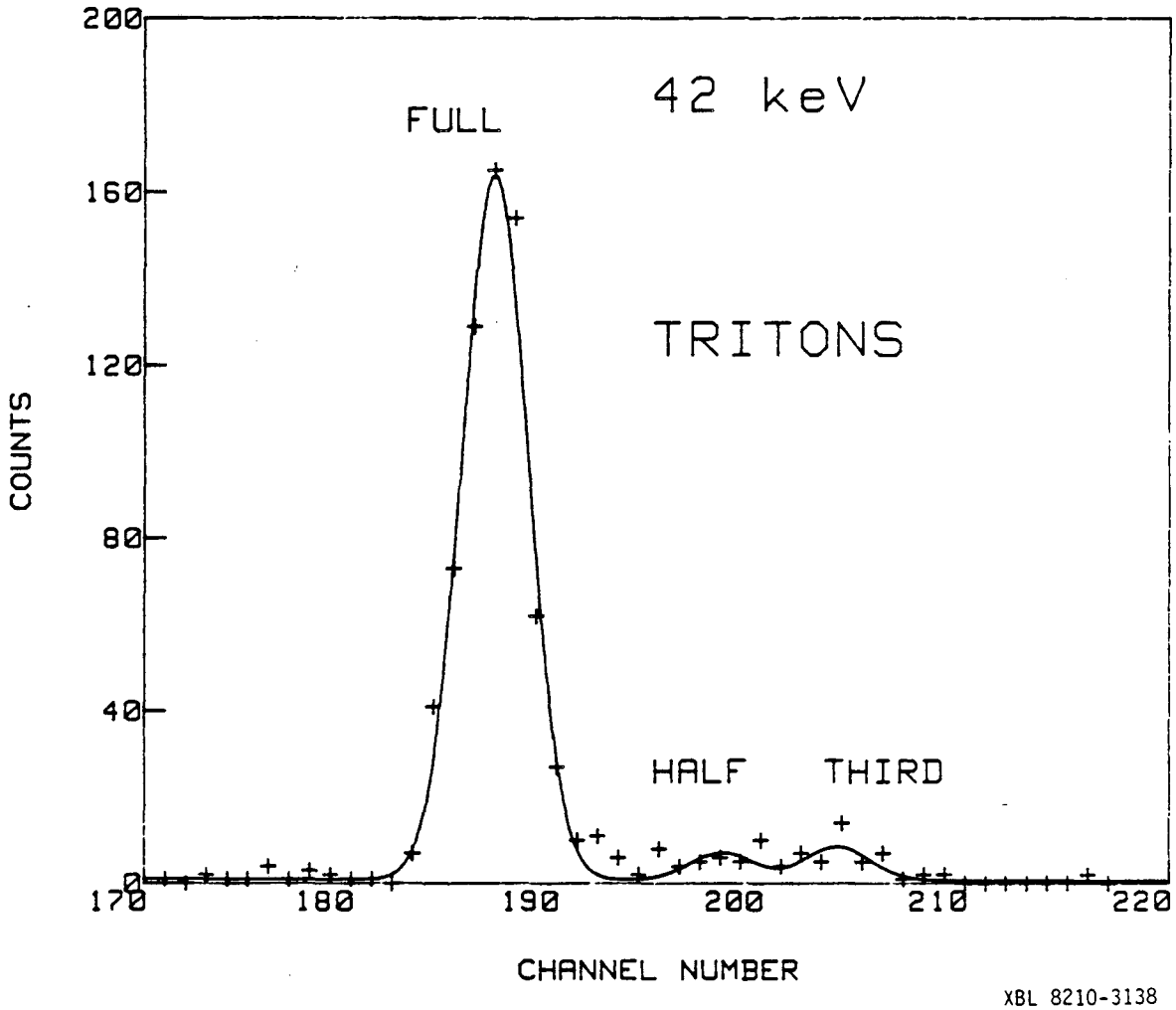
GAUSSIAN-FITTED SPECTRUM OF FULL, HALF, AND THIRD ENERGY FUSION TRITONS FROM A 63-kV DEUTERIUM BEAM INCIDENT ON A DEUTERIUM GAS TARGET.

Fig. 3c



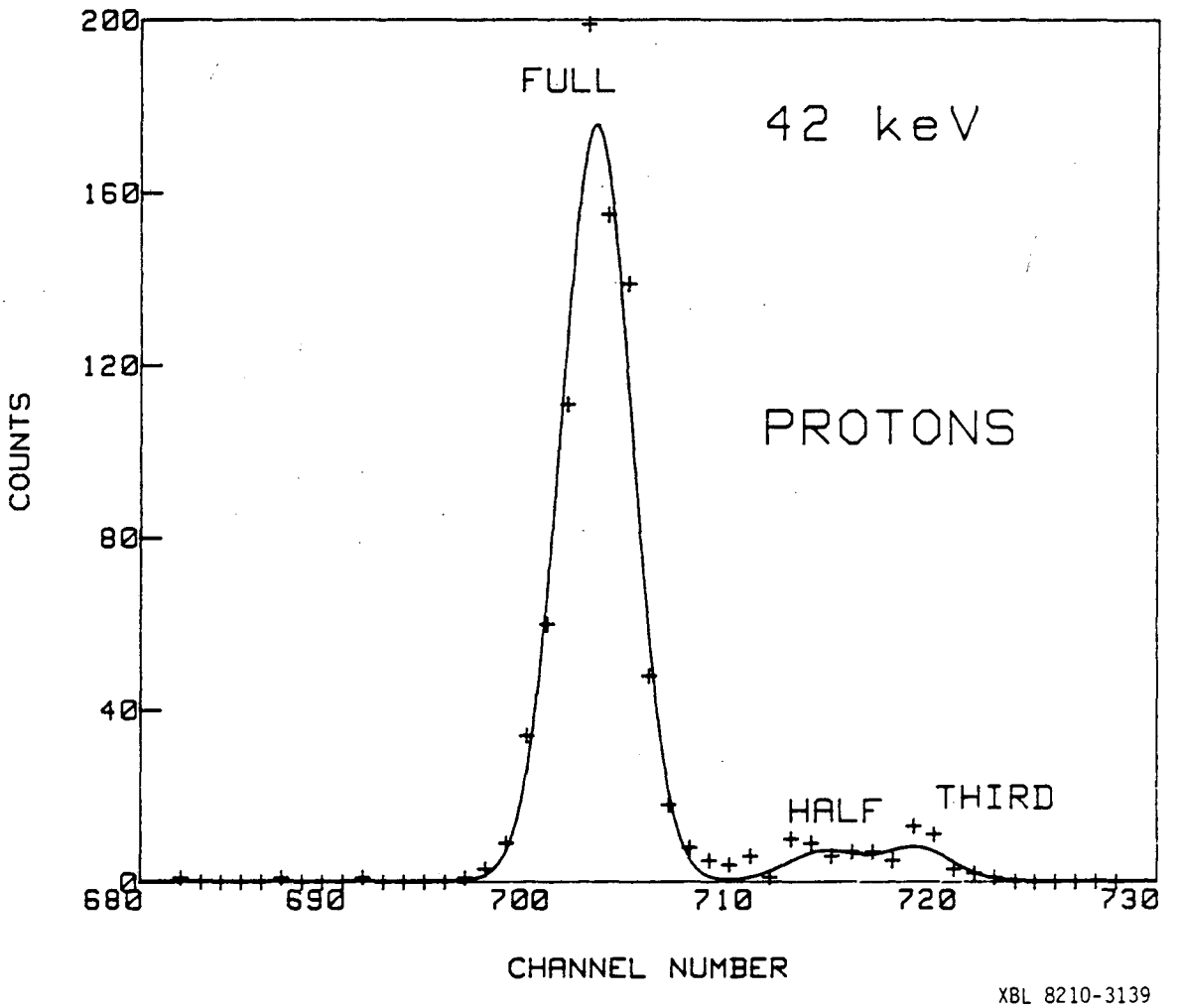
GAUSSIAN-FITTED SPECTRUM OF FULL, HALF, AND THIRD ENERGY FUSION PROTONS FROM A 63-kV DEUTERIUM BEAM INCIDENT ON A DEUTERIUM GAS TARGET.

Fig. 3d



GAUSSIAN-FITTED SPECTRUM OF FULL, HALF, AND THIRD ENERGY FUSION TRITONS FROM A 42-kV DEUTERIUM BEAM INCIDENT ON A DEUTERIUM GAS TARGET.

Fig. 3e



GAUSSIAN-FITTED SPECTRUM OF FULL, HALF, AND THIRD ENERGY FUSION PROTONS FROM A 42-kV DEUTERIUM BEAM INCIDENT ON A DEUTERIUM GAS TARGET.

Fig. 3f

Incident Energy (keV)	Deuterium Fraction (%) Full	Half	Third	Proton/Triton/OMA
43	47 ± 5	9 ± 2	44 ± 6	Triton
	49 ± 6	9 ± 2	46 ± 6	Proton
	64 ± 4	7 ± 3	29 ± 3	OMA
63	65 ± 3	14 ± 1	21 ± 2	Triton
	63 ± 3	14 ± 1	22 ± 2	Proton
	77 ± 4	10 ± 3	13 ± 3	OMA
82	73 ± 2	15 ± 1	12 ± 1	Triton
	71 ± 2	16 ± 1	13 ± 1	Proton
	81 ± 4	13 ± 3	7 ± 3	OMA

Table 1

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