Using values of D determined as above and using 703 barns[1] for boron, one obtains cross sections for He^3 and N from relation (1). The values so obtained, as listed in the last column of Table I, are:

$$\sigma_{He^3}(n,p) = 5040 \pm 200$$

and

$$\sigma_N(n,p) = 1.76 \pm 0.05 \text{ barns.}$$

Since the value of 703 barns applies to neutrons of 2200 meters per second or 293°K, the present determination applies to neutrons of this same energy even though there may have been a distorted spectrum in the region of the counter.

The second He^3 filling partially leaked out of the counter before any data were obtained. Counting with this unknown quantity of He^3 and assuming none was lost gave a value of $\sigma = 3850$ barns. Correcting this for the estimated loss gave a value of 5000 ± 1000.

The largest error was in the extrapolation of the pulse height distribution curves to zero and in evaluation of the number of small pulses. However, three sets of data on the good He^3 filling taken under somewhat different conditions and at intervals one week separated gave values with a total spread of only 2.3 percent. The data-taking was intermittent and extended over a period of three months, beginning and ending with the two nitrogen runs. Counting rates were such that statistical errors were negligible.

Values of the absorption cross section of nitrogen have been determined by Lapointe and Rasetti[5] and by Lichtenberger *et al.*[4] who obtained 1.4 ± 25 percent and 1.72 barns, respectively. These values have been adjusted so as to be dependent on a boron absorption cross section of 703. Comparison with the present measured value of 1.76 ± 0.05 for the n-p disintegration process gives a limit to the probability of other processes competing with the n-p process.

Note added in proof: Since submission of this manuscript two papers on the He^3 reaction have appeared in the literature. King and Goldstein,[11] from measurements with pure He^3 samples, obtain a value of 5000 barns for the total cross section of He^3 for 293° neutrons. This is in good agreement with the present value. In England, Batchelor *et al.*,[12] working with the very low concentration of He^3 in normal "atmospheric" helium, measure a cross section value of 3700 barns for the n-p reaction. They quote an error of ±250 barns plus whatever uncertainties there are in the values they used for the $N(n,p)$ reaction and for the He^3 isotopic abundance in their gas sample. The best information on these quantities does not reconcile the discrepancy between our value and the British value.

ACKNOWLEDGMENT

Thanks are due to E. R. Graves and to R. F. Taschek for helpful criticisms, and to R. W. Davis for help in carrying out the measurements.

[11] L. D. P. King and Louis Goldstein, Bull. Am. Phys. Soc. **24** (1), 31 (1949); also Phys. Rev. **75**, 1366 (1949).
[12] R. Batchelor, J. S. Epstein, B. H. Flowers, and A. Whittaker, Nature **163**, 211 (1949).

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A Study of the Interaction of Protons with Tritium*

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Preliminary measurements of the scattering cross section of tritium for protons and the reaction cross section for $T^3(p,n)He^3$ have been made. A method of analysis for hydrogen in tritium samples is described. The neutron yield of the reaction is high and will make it a useful source; the threshold is sharp and can be used as a point on the energy scale of nuclear physics. Angular distributions for scattering and cross sections for the reaction are given.

INTRODUCTION

THIS is a preliminary report on experience with the interaction of protons and tritium for proton energies between 900 kev and 2.5 Mev as accelerated by the Los Alamos electrostatic generator. Tritium gas targets were used, the particular design reported elsewhere,[1] although this target has no immediate advantage for some of the work reported here.

* This document is based on work performed under U. S. Government Contract Number W-7405-Eng-36 at the Los Alamos Scientific Laboratory of the University of California.
[1] R. F. Taschek, Rev. Sci. Inst. **19**, 591 (1948).

GAS HANDLING SYSTEM

Because of the small volume of precious gas available special methods of handling it were devised. Figure 1 is a schematic diagram of the tritium storage and handling system used; heated uranium shavings provided a completely satisfactory method of evolving the tritium-hydrogen mixture stored as hydride in the cold uranium when not in use. Titanium would probably have been as satisfactory. In case of small air or counter argon leaks into the target the uranium also acts

as a purifier for the hydrogen gases. Since the total amount of gas available was only about 10 cm³ at N.T.P., the mercury lift through the 500 cm³ bulb was used to make a complete transfer of gas at maximum efficiency from uranium pump to target and *vice versa* possible. Auxiliary connections could be made to suppplies of hydrogen and deuterium gas as shown in Fig. 1.

To guard against the possibility of breaking one of the thin aluminum foils sealing the target gas from accelerating tube vacuum and thus losing it, the "gas impedance" tube and trip valve shown schematically in Fig. 2 were used to connect target to accelerating tube. This device was to work by having the increase in gas pressure resulting from a broken foil fire either an ion gauge or spark plug, which in turn would trip the valve at the other end of the tube before an appreciable amount of the gas escaped through the high impedance flow tube. The gas was then to be recovered with the uranium pump. Up to the present time this device has not had the necessity for firing under the conditions for which it was designed.

ANALYSIS OF TRITIUM SAMPLES FOR HYDROGEN

In order to obtain absolute cross sections for particle interactions with tritium, it is necessary to know the amount of contaminating hydrogen (a product of the manufacturing process) with good accuracy. Early methods of analysis were quickly found to be unreliable and it was decided that 45° proton-proton scattering could be used to determine the amount of hydrogen. The following method was used for the analysis: tank hydrogen was first put into the target at about 10 cm mercury pressure, accurately measured. At a bombarding energy of about 2 Mev, the 45° scattered protons were counted. The shape of the pulse height distribution was recorded by a 10 channel pulse height analyser[2] with the Los Alamos Model 100 amplifier gain set so the peak of the distribution fell in the highest channels. Now leaving all variables unchanged but the gas, which was replaced to about the same pressure from the tritium sample a second pulse height distribution was recorded for the same number of microcoulombs of protons as in the hydrogen run. In Fig. 3 are shown typical pulse height distributions for tank hydrogen and for our tritium sample; smooth curves have been drawn through the total counts in each channel at the channel center for ease of representation. For the scattering from the tritium sample a double peak is observed, the smaller pulse height group corresponding to protons scattered from tritium, the

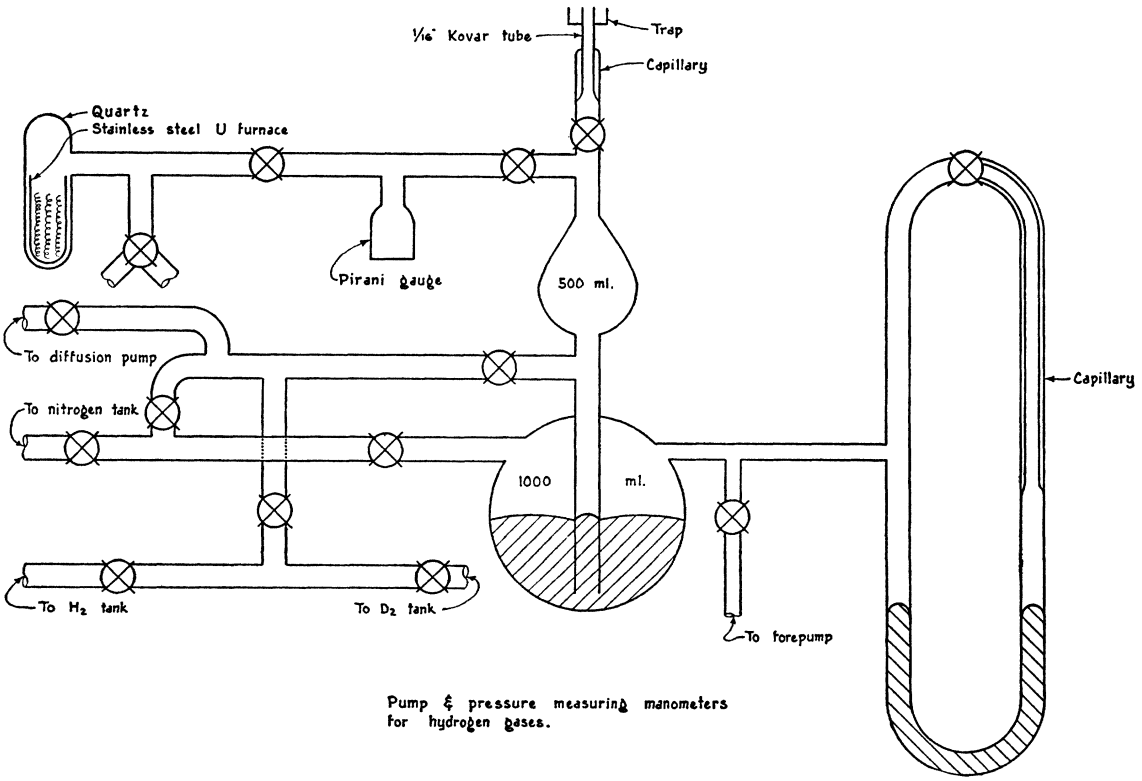

FIG. 1. Tritium storage and gas handling system.

[2] Los Alamos Technical Series *I*, Part 1, Section 4.5.

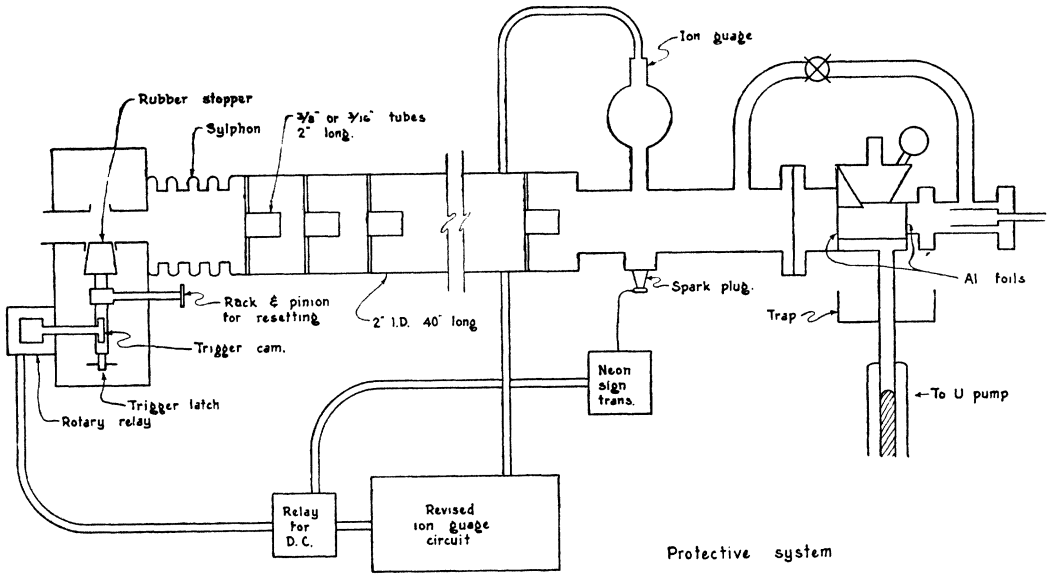

FIG. 2. Gas impedance tube and circuits for tritium recovery in case of foil breakage on target.

larger corresponding to hydrogen scattered protons; in this case counter pressure was set to make the energy loss from hydrogen scattered protons larger. With no further information than this, a direct comparison of the number of protons per centimeter of Hg target gas pressure under the tank hydrogen peak with the number under the hydrogen peak of the tritium sample gives the hydrogen concentration in the sample, from which the tritium concentration is immediately obtained. Concentration of tritium in the sample used here was 62 ± 2 percent obtained from three separate analyses. To check whether the sampling out of the tritium storage pump was adequate, the first and last analyses were made when only the minimum necessary gas was evolved, while the middle analysis was obtained from gas taken out of a complete evolution of the sample. Mean deviation of the three analyses was about one percent.

Obviously a very good analysis would require a palladium leaked hydrogen sample for a standard, but for the immediate needs this was not considered necessary. As a check on the method, one of the tank hydrogen runs was used to calculate a value of the proton-proton scattering cross section at 45°, since this is accurately known. Without attempting to correct for partial pressures of contaminating gases in tank hydrogen a cross section of 0.45_8 barn per unit solid angle was obtained comparing favorably with 0.472 barns given by Herb and his collaborators.[3] This measurement, in addition to checking the adequate purity of the hydrogen, is also a check on the accuracy of the proton detecting geometry factor of the proportional counter and indicates that measurement and calculation of this factor is correct to a few percent.

Considerable experience during the past year has shown that the gaseous tritium sample is not stable in our target against chemical exchange with hydrogen in stopcock grease. Using outgassed Apiezon *N* grease, this is most clearly shown by a progressive decrease in the tritium scattered protons and a corresponding increase in the hydrogen scattered protons. The use of a completely fluorinated grease did not greatly help since the tritium concentration still decreased, although the hydrogen concentration changed only slightly. It seems clear that this exchange phenomenon is greatly enhanced by passage of the beam through the target, since a sample left in the target overnight showed less than half the concentration change it

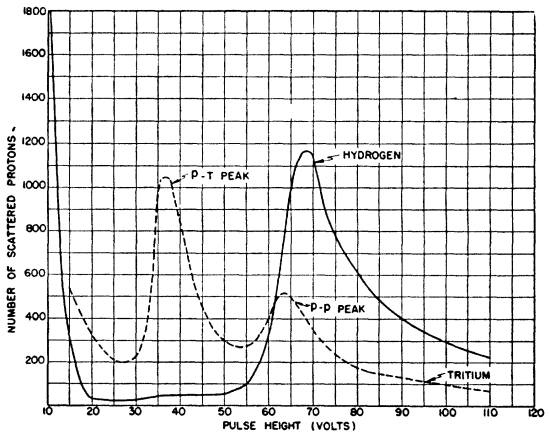

FIG. 3. Pulse height distribution of protons scattered from a tritium sample and from tank hydrogen.

[3] Herb, Kerst, Parkinson, and Plain, Phys. Rev. **55**, 998 (1939).

TABLE I. Cross sections at 2.0 Mev.

Laboratory angle θ	Center of mass angle ϕ	$\sigma(\theta)$ in barns per unit solid angle	$\sigma(\phi)$
45°	50°	0.325	0.217
67½°	86°	0.189	0.154
90°	109° 30′	0.145	0.154

would have experienced in the same interval with a one microampere beam passing through it.

P-T SCATTERING CROSS SECTION

In part a by-product of the analysis problem, three values of the scattering cross section of protons on tritium have been obtained at 2.01 Mev and an angular distribution of scattering between 45° and 135° at 1.59 Mev. These values are in absolute units based on the concentration measurements above. Table I lists the cross sections obtained at 2.0 Mev and Fig. 4 shows the laboratory and center of mass angular distributions at 1.59 Mev with the 2.0 Mev data also plotted.

It appears that for these two energies the differential cross sections are quite similar in value for the angular range in which measurements were made. The value of $\sigma_{P-T}(86°)$ of 0.154 may be compared with $\sigma_{P-P}(90°)=0.167$, both near 90° in the center of mass system.

It is obvious from the data that in the angular range shown the differential cross section is primarily caused by nuclear scattering. The general trend with angle and even absolute cross section is rather similar to that found in *p-d* scattering.[4] The absolute cross sections are probably good to only about 10 percent, the relative values to 5 percent or less. A more detailed and precise investigation of the scattering is to be undertaken in the near future. This work will be greatly facilitated by the higher tritium concentration available.

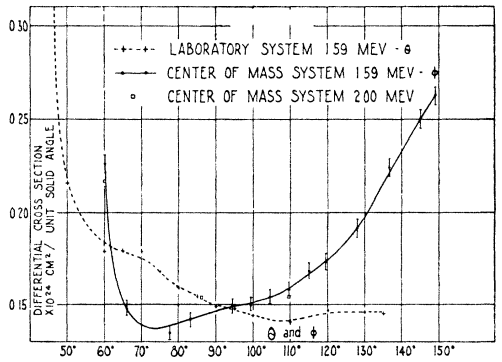

FIG. 4. Laboratory and center of mass system differential cross section of protons scattered from tritium.

[4] Sherr, Blair, Kratz, Bailey, and Taschek, Phys. Rev. **72**, 662 (1947).

THE REACTION $T^3(p,n)He^3$

The fiducial point of the energy scale of our Van de Graaff generator in the past has been the threshold of the $Li^7(p,n)Be^7$ reaction,[5] because the extremely sharp rise in neutron yield allows an accurate determination of voltage on the electrostatic analyzer scale. The proton energy of this threshold has been assumed to be 1.86_0 Mev, a value determined by the Westinghouse generator[6] relative to presumably known energies at certain (p,γ) resonances. By direct measurement on a curved plate electrostatic analyzer and voltage supply Hanson and Benedict[7] found 1.883 Mev for the same threshold; a value of 1.889 ± 0.004 was also obtained in this laboratory with an improved analyzer and voltage supply.** The existence of this large a discrepancy in the energy scale is a serious one both for the effect on neutron energies from endoergic reactions and even more so for the whole energy scale of nuclear physics.

If one now considers the system of reactions

$$T^3\rightarrow He^3+\tilde{\beta}+15 \text{ kev}, \quad T^3-He^3=15 \text{ kev}$$

and

$$p+T^3\rightarrow He^3+n-Q,$$

we find that in the laboratory system

$$Ep=4/3Q=4/3\{(n-p)-(T^3-He^3)\}.$$

Assuming that the neutron-proton mass difference is 755 kev,[8,9] then $Ep=986$ kev for the threshold of $T^3(p,n)He^3$. This shows that either of two things may be done; first, if the energy scale were very precisely known an extremely good value of the neutron-proton mass difference could be obtained by measuring proton energy at threshold even if the T^3-He^3 mass difference is known to only 20 percent or so; secondly, one may assume that, under the present circumstances, the *n-p* mass difference is known as well as the energy scale and in this way calibrate the latter. It was in this way that we redetermined our energy scale, the primary difficulty being, for our target, the thickness of the aluminum window at about one Mev. Using the calculated energy loss in the foil at one Mev, 185 kev, it appears that our energy scale based on 1.86 Mev for the $Li^7(p,n)Be^7$ threshold is about 25 kev too low, but if 1.89 Mev is used, the observed threshold for $T^3(p,n)He^3$ comes to 990 kev, which is about correct. This measurement is to be repeated

[5] R. F. Taschek and Arthur Hemmendinger, Phys. Rev. **74**, 373 (1948).
[6] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **58**, 1035 (1940).
[7] A. O. Hanson and D. L. Benedict, Phys. Rev. **65**, 33 (1944).
** Herb, Snowden, and Sala [Phys. Rev. **75**, 246 (1949)] report a recent and precise value of 1.882 Mev for this threshold.
[8] D. J. Hughes, Phys. Rev. **70**, 219 (1946).
[9] W. E. Stephens, Rev. Mod. Phys. **19**, 19 (1947).

with condensed tritium targets. At present the best determination of foil thickness is obtained by assuming the energy of the reaction threshold to be 986 kev and an energy scale based on 1.89 Mev for $Li^7(p,n)Be^7$.

Figure 5 shows the differential cross section for the reaction between threshold and about 2.2 Mev proton energy in the target gas for 0° and 90° in the laboratory system. The neutron yields were measured with eight inch long-counters[10] at distances of two meters from the source in order that near threshold no effects purely due to geometry be introduced. The long counters were calibrated with a standardized radium-beryllium source placed at the target position. It is believed that the cross sections are good to only about ±10 percent over most of the range because the target geometry is such that, for these relatively low energy neutrons, a rather large amount of scattering material is close to the source and not completely symmetrically disposed. Experience with measuring angular distributions would indicate that the zero degree data may be as much as 10 percent too high compared to 90°. The angular distributions are to be repeated in detail using a target assembly with a minimum of scattering material in the vicinity.

The advantages of $T^3(p,n)He^3$ as a monoenergetic neutron source are apparent, particularly with a low energy machine. With the present generator capable of about 2.7 Mev, neutrons up to 1.8 Mev can be obtained while only about one Mev neutrons are available from the $Li^7(p,n)Be^7$ reaction. In addition to this, the *cone*[5] of neutrons at threshold has 60 kev energy, making another strong neutron cone source available besides the 30 kev neutrons from $Li^7(p,n)Be^7$, which is very important for certain types of experiments. It should be pointed out that the cross sections obtained here are large and compare favorably indeed with those from $Li^7(p,n)Be^7$. The trend of the yield with energy indicates even larger yields above the maximum reached here.

It is not useful to compare center of mass cross sections since 90° in the laboratory changes continuously with energy in the center of mass system. As an example, however, at 2 Mev

$\theta=0°$	$\phi=0°$
$\sigma(\theta)=0.062$ barns,	$\sigma(\phi)=0.029$
$\theta=90°$	$\phi=117°$
$\sigma(\theta)=0.031$,	$\sigma(\phi)=0.035$

[10] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

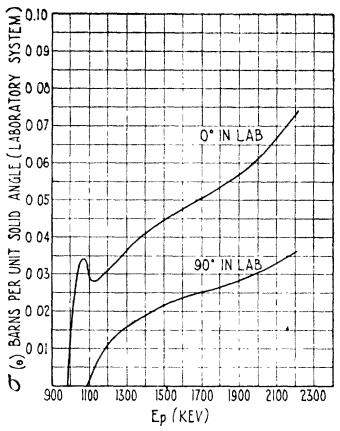

FIG. 5. 0° and 90° laboratory differential cross sections of $T^3(p,n)He^3$ as a function of proton energy.

indicating a rather symmetric distribution in the center of the mass system which is borne out by preliminary angular distributions at 1.2, 1.5, and 1.8 Mev. The peak in the 0° cross section data just above threshold is probably due primarily to the fact that up to $Ep=120$ kev above threshold all neutrons lie within some cone of half-angle less than 90°, due to center of mass motion, but above this energy they suddenly spread out over 4π solid angle resulting in a decrease in the 0° yield. A very similar phenomenon is observed in the corresponding lithium reaction, although possibly not so clean cut. It will be noted that there is no 90° yield until just at the turn over of the 0° curve.

One can feel reasonably certain that for proton energies even considerably larger than those used here the neutrons will remain monoergic. This arises from the knowledge that the neutrons from $D(d,n)He^3$ are monoergic at least up to 2.5 Mev deuteron energy and the residual nucleus He^3 is the same in both cases, meaning that no excited states of He^3 have been observed up to an excitation energy of over 20 Mev for the compound nucleus He^4.

With the measurement of the cross section of the inverse reaction $He^3(n,p)T^3$, a rather good check of the principle of detailed balance should be possible. Preparations are also underway to investigate $T^3(p,\gamma)He^4$ which has a Q of approximately 19 Mev and should complete the low energy proton interactions with tritium.