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HIGH-ENERGY NEUTRONS PRODUCED
BY 740-MEV PROTONS ON URANIUM

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I. INTRODUCTION

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TODAY I WOULD LIKE TO PRESENT SOME MEASUREMENTS OF HIGH-ENERGY NEUTRON SPECTRA PRODUCED BY 740 MEV PROTON BOMBARDMENT OF A THICK URANIUM TARGET. THE GENERAL PURPOSE OF THESE MEASUREMENTS WAS TO TEST THE DEGREE OF VALIDITY OF THE PREDICTIONS OF MONTE CARLO CALCULATIONS BASED ON THE INTRANUCLEAR CASCADE MODEL. THE SPECIFIC OBJECTIVE OF THESE MEASUREMENTS WAS TO TEST THE VALIDITY OF CALCULATIONS MADE FOR THE DEVELOPMENT OF AN INTENSE PULSED NEUTRON SOURCE USING PROTONS FROM THE LAMPF ACCELERATOR. FOR THIS PURPOSE, AN EXPERIMENT WAS SET UP BY LOS ALAMOS (LASL) AT THE LAWRENCE BERKELEY LABORATORY 184-INCH CYCLOTRON TO MEASURE THE NEUTRON SPECTRA AT 50 AND 130 DEGREES FROM 740 MEV PROTON BOMBARDMENT OF A 30 CM THICK DEPLETED URANIUM TARGET. WE WERE INVITED TO PARTICIPATE IN THESE MEASUREMENTS AND, IN PARTICULAR, TO MEASURE THE HIGH-ENERGY OR CASCADE REGIONS OF THE SPECTRA. TODAY, I WILL REPORT THE RESULTS OF MEASUREMENTS MADE FROM 20 TO 500 MEV AT

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50 DEGREES AND FROM 5 TO 140 MEV AT 130 DEGREES WITH RESPECT
TO THE PROTON BEAM. } MEASUREMENTS OF THE LOW-ENERGY
SPECTRA FROM 60 KEV TO 10 MEV WERE MADE WITH DIFFERENT
DETECTION TECHNIQUES BY DR. LYNN VEESER AND HIS COLLABORATORS¹
FROM LOS ALAMOS.

PRIOR TO THESE MEASUREMENTS, THE UNPUBLISHED DATA OF
FRASER AND HIS COLLABORATORS² REPRESENT THE ONLY MEASUREMENTS
AVAILABLE ON NEUTRON SPECTRA FROM HEAVY-METAL TARGETS AT
PROTON BOMBARDING ENERGIES ABOVE THE PION PRODUCTION
THRESHOLD. FRASER AND HIS COLLABORATORS MEASURED THE
NEUTRON SPECTRA FROM 1 GEV PROTON BOMBARDMENT OF A THICK
LEAD TARGET IN CONNECTION WITH THE CANADIAN INTENSE NEUTRON
GENERATOR (ING) STUDY; HOWEVER, THESE MEASUREMENTS WERE
LIMITED TO NEUTRON ENERGIES BELOW 150 MEV.

II. THE SPECTROMETER (SLIDE 1)

THE MEASUREMENTS TO BE REPORTED HERE WERE MADE WITH A SELF-CONTAINED TIME-OF-FLIGHT SPECTROMETER WHICH WE HAVE DEVELOPED FOR NEUTRON ENERGIES FROM 1 TO ABOUT 500 MEV. THIS SPECTROMETER IS SHOWN SCHEMATICALLY IN THE FIRST SLIDE.

BASICALLY, THE SPECTROMETER CONSISTS OF TWO PRIMARY SCINTILLATION COUNTERS D1 AND D2, AND TWO ANTICOINCIDENCE DETECTORS A1 AND A2. THE PRINCIPLE OF THE SPECTROMETER REQUIRES AN INCIDENT NEUTRON TO SCATTER ELASTICALLY THROUGH AN ANGLE θ FROM A PROTON IN THE D1 SCINTILLATOR. THE SCATTERED NEUTRON MUST THEN TRAVEL OVER A KNOWN FLIGHT PATH X AND INTERACT IN THE D2 SCINTILLATOR. THE TIME-OF-FLIGHT OF THE SCATTERED NEUTRON IS THE TIME INTERVAL BETWEEN SCINTILLATION PULSES FROM THE NEUTRON INTERACTIONS IN THE D1 AND D2 SCINTILLATORS. THE INCIDENT NEUTRON ENERGY IS SPECIFIED BY THE TIME-OF-FLIGHT, THE FLIGHT PATH, AND THE SCATTERING ANGLE OF THE SCATTERED NEUTRON. THE A1

AND A2 ANTICOINCIDENCE DETECTORS VETO EVENTS RESULTING FROM CHARGED PARTICLES IN THE INCIDENT AND SCATTERED NEUTRON BEAMS.

BACKGROUND FROM NEUTRON-CARBON INTERACTIONS IN THE D1 SCINTILLATOR IS SUBTRACTED BY MEASURING THE SPECTRUM TWICE WITH D1 SCINTILLATORS WHICH DIFFER SIGNIFICANTLY IN THEIR RELATIVE HYDROGEN-CARBON COMPOSITION. [FOR THIS PURPOSE WE HAVE USED NE-102 PLASTIC AND NE-228 LIQUID SCINTILLATORS, FOR NEUTRON ENERGIES ABOVE ABOUT 15 MEV, WE HAVE USED A 9 IN. DIAM BY 8 IN. HIGH NE-102 PLASTIC SCINTILLATOR FOR THE D2 DETECTOR. THE D1 DETECTOR DIMENSIONS ARE TYPICALLY 2 1/2 IN. DIAM BY 2 1/1 IN. HIGH.]

IV. TIME-OF-FLIGHT SPECTRA (SLIDE 2)

THE NEXT SLIDE SHOWS A TYPICAL TIME-OF-FLIGHT MEASUREMENT. SPECIFICALLY, THIS SLIDE SHOWS THE TIME-OF-FLIGHT SPECTRUM OF NEUTRONS FROM 15 TO ABOUT 140 MEV WHICH WAS MEASURED AT 130 DEGREES WITH RESPECT TO THE PROTON BEAM. THE ORDINATE IS COUNTS PER CHANNEL. THE ABSCISSA GIVES

THE CHANNEL NUMBER. THE FLIGHT-TIME INCREASES WITH INCREASING CHANNEL NUMBER. THE NARROW PEAK IS THE GAMMA-RAY SPECTRUM; THE BROAD CENTRAL PEAK IS THE NEUTRON SPECTRUM. THE FLAT REGIONS TO THE LEFT AND RIGHT OF THE TIME-OF-FLIGHT PEAKS INDICATE THE LEVEL OF ACCIDENTAL COINCIDENCES. THE GAMMA-RAY PEAK SERVES AS A TIME-OF-FLIGHT REFERENCE FOR ENERGY CALIBRATION OF THE SPECTRUM.

V. COMPARISON WITH THE MONTE CARLO CALCULATION (SLIDE 3)

THE NEXT SLIDE SHOWS OUR RESULTS AND THE MONTE CARLO CALCULATIONS AT BOTH 50 AND 130 DEGREES. THE ORDINATE IS THE DIFFERENTIAL NEUTRON YIELD EXPRESSED IN NEUTRONS PER PROTON-SR-MEV. THE ABSCISSA IS THE NEUTRON ENERGY IN MEV. THE HISTOGRAMS REPRESENT THE CALCULATED SPECTRA AVERAGED OVER THE INTERVALS FROM 33 TO 60 DEGREES AND FROM 120 TO 147 DEGREES. THIS CALCULATION WAS MADE WITH THE NUCLEON-MESON TRANSPORT CODE (NMTC)³ FOR 800 MEV PROTONS ON AN URANIUM TARGET OF THE SAME DIMENSIONS. THE ERROR BARS ON THE EXPERIMENTAL DATA REPRESENT THE STATISTICAL UNCERTAINTY IN THE

MEASUREMENT. THE ENERGY RESOLUTION OF THE SPECTROMETER FOR THESE MEASUREMENTS WAS TYPICALLY BETWEEN 10 AND 20 PERCENT DEPENDING UPON THE NEUTRON ENERGY.

THE SHAPE OF THE EXPERIMENTAL AND CALCULATED SPECTRA ARE IN GENERAL AGREEMENT. FOR NEUTRONS ABOVE 25 MEV, THE MEASURED YIELD AT 50 DEGREES IS 5 TIMES GREATER THAN THAT AT 130 DEGREES. THE GREATER YIELD IN THE FORWARD DIRECTION IS A RESULT OF THE FORWARD PEAKING OF THE CASCADE NEUTRONS.

BELOW 20 MEV, THE RESULTS ARE IN AGREEMENT WITH THE MONTE CARLO CALCULATION. AT BOTH 50 AND 130 DEGREES, THE MAGNITUDE OF THE MEASURED SPECTRUM OF CASCADE NEUTRONS IS GREATER THAN CALCULATED. AT 50 DEGREES, THE YIELD ABOVE 25 MEV IS 1.3 TIMES GREATER THAN CALCULATED; AT 130 DEGREES, THIS FACTOR INCREASES TO 1.6.

COMPARISON⁴ OF THE THICK LEAD TARGET DATA OF FRASER AND COLLABORATORS WITH THE PREDICTIONS OF THE NUCLEON-MESON TRANSPORT CODE SHOWS A SIMILAR BUT MORE SERIOUS DISCREPENCY.

FROM 30 TO 150 MEV, AGREEMENT BETWEEN EXPERIMENT AND THE CALCULATION IS GOOD AT 45 DEGREES, FAIR AT 90 DEGREES, AND POOR AT 135 DEGREES. AT 135 DEGREES, THE MEASURED YIELD IS ESTIMATED TO BE THREE TIMES GREATER THAN CALCULATED. BERTINI⁵ HAS COMPARED THE PROTON SPECTRA OF AZHGIREY AND COLLABORATORS⁶ FROM 660 MEV PROTONS ON A THIN URANIUM TARGET [7.62 G/CM²] WITH THE PREDICTIONS OF THE INTRANUCLEAR CASCADE MODEL. COMPARISONS WERE MADE AT 12, 18, AND 30 DEGREES. AGREEMENT AT 12 AND 18 DEGREES IS GOOD; AT 30 DEGREES, THE MAGNITUDE OF THE MEASURED SPECTRUM IS GREATER. OUR MEASUREMENTS CONFIRM THIS TENDENCY FOR THE MAGNITUDE OF THE CALCULATED SPECTRUM TO FALL BELOW THE MEASURED SPECTRUM AS THE ANGLE OF OBSERVATION IS INCREASED.

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