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NEUTRON SPECTROMETRY
FROM 1 MEV TO 1 GEV

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INTRODUCTION

AT THE INTERNATIONAL SYMPOSIUM ON "NUCLEAR ELECTRONICS AND RADIO-PROTECTION" AT TOULOUSE, FRANCE, IN MARCH 1968 NEARLY FIVE YEARS AGO, I GAVE A BRIEF DESCRIPTION OF A SELF-CONTAINED TIME-OF-FLIGHT SPECTROMETER FOR NEUTRONS IN THE ENERGY REGION FROM 10 TO 100 MEV.⁽¹⁾ ABOUT THREE YEARS AGO (IN NOVEMBER 1969) AT THE SECOND INTERNATIONAL CONFERENCE ON ACCELERATOR RADIATION DOSIMETRY AND EXPERIENCE HELD AT THE STANFORD LINEAR ACCELERATOR CENTER IN CALIFORNIA, I PRESENTED RESULTS OF SOME OBSERVATIONS OF THE PERFORMANCE OF THE SPECTROMETER WITH 14 MEV NEUTRONS FROM THE NEUTRON GENERATOR FACILITY AT THE NATIONAL RESEARCH COUNCIL IN OTTAWA, CANADA.⁽²⁾ TODAY, I SHALL PRESENT THE RESULTS OF SOME MEASUREMENTS MADE DURING THE PAST TWO YEARS AT THE 184-INCH CYCLOTRON AT THE LAWRENCE BERKELEY LABORATORY. IN JANUARY AND MARCH OF 1971, WE HAD SUCCESSFUL EXPERIENCES MEASURING NEUTRON SPECTRA IN THE ENERGY REGION FROM 1 TO 500 MEV. MORE RECENTLY IN SEPTEMBER OF THIS YEAR, WE HAVE USED A MODIFIED VERSION OF THE SPECTROMETER TO MEASURE NEUTRON SPECTRA PRODUCED AT ZERO DEGREES

MASTER

FROM 724 MEV PROTONS ON BERYLLIUM AND COPPER TARGETS.

PRINCIPLE (SLIDE 1)

THE SPECTROMETER IS SHOWN SCHEMATICALLY IN THE FIRST SLIDE. BASICALLY, THE SPECTROMETER CONSISTS OF TWO PRIMARY SCINTILLATION COUNTERS D1 AND D2. 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 FROM KINEMATICS 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.

THE LOW-ENERGY LIMIT OF THE SPECTROMETER IS DEFINED BY THE ABILITY TO DETECT RECOIL PROTONS IN THE D1 DETECTOR WITH 100 PERCENT EFFICIENCY. THE HIGH-ENERGY LIMIT OCCURS IN PRACTICE AT

ABOUT 500 MEV WHEN THE BACKGROUND BECOMES SIGNIFICANT FROM NEUTRON-PROTON INELASTIC SCATTERING REACTIONS. BACKGROUND FROM NEUTRON-CARBON INTERACTIONS IN THE D1 SCINTILLATOR IS DETERMINED FROM SEPARATE MEASUREMENTS MADE WITH D1 SCINTILLATORS THAT DIFFER SIGNIFICANTLY IN THEIR RELATIVE HYDROGEN-CARBON COMPOSITIONS.

EFFICIENCY AND RESOLUTION (SLIDE 2)

TYPICAL VALUES OF THE EFFICIENCY AND THE ENERGY RESOLUTION OF THE SPECTROMETER ARE SHOWN IN THE NEXT SLIDE (#2). THE ORDINATE IS THE SPECTROMETER EFFICIENCY, WHICH IS DEFINED AS THE NUMBER OF NEUTRONS DETECTED TO THE NUMBER OF NEUTRONS INCIDENT ON THE D1 DETECTOR. THE ABSCISSA IS THE ENERGY RESOLUTION OF THE SPECTROMETER. THE CURVE REPRESENTS THE VALUES OF THE EFFICIENCY AND THE RESOLUTION FOR A NEUTRON FLIGHT-PATH OF 5 METERS AND A NEUTRON SCATTERING ANGLE OF 40 DEGREES. THESE VALUES OF THE EFFICIENCY AND THE RESOLUTION WERE COMPUTED FOR A SPECTROMETER CONSISTING OF A 2 1/2 INCH DIAMETER BY 2 1/2 INCH HIGH FIRST (D1) DETECTOR AND A 9 INCH DIAMETER BY 8 INCH THICK SECOND (D2) DETECTOR. -- (FOR A GIVEN NEUTRON ENERGY, THE EFFICIENCY DECREASES WITH INCREASING FLIGHT

PATH; ON THE OTHER HAND, THE ENERGY RESOLUTION IMPROVED WITH INCREASING FLIGHT-PATH. THE SPECTROMETER CONFIGURATION FOR ANY MEASUREMENT REPRESENTS A COMPROMISE BETWEEN COUNT RATE AND RESOLUTION.) FOR A FLIGHT PATH OF 5 METERS, THE EFFICIENCY VARIES FROM ABOUT 1.5×10^{-5} AT 10 MEV TO ABOUT 4×10^{-7} AT 1 GEV, AND THE ENERGY RESOLUTION VARIES FROM 5 PERCENT AT 10 MEV TO 25 PERCENT AT 1 GEV. THE RESOLUTION FOR HIGH-ENERGY NEUTRONS CAN, OF COURSE, BE IMPROVED CONSIDERABLY BY USING LONGER FLIGHT-PATHS.

MEASUREMENT OF 220 MEV NEUTRONS (SLIDE 3)

THE NEXT SLIDE (#3) SHOWS THE RESULTS OF A MEASUREMENT OF 220 MEV NEUTRONS PRODUCED BY STRIPPING 447 MEV DEUTERONS ON A 3/8-INCH BERYLLIUM TARGET (IN THE 184-INCH CYCLOTRON AT THE LAWRENCE BERKELEY LABORATORY.) THE ORDINATE IS THE NUMBER OF EVENTS PER MEV; THE ABSCISSA IS THE NEUTRON ENERGY IN MEV. THE DASHED CURVE IS THE THEORETICAL SPECTRUM⁽³⁾ BROADENED BY THE SPECTROMETER RESOLUTION. COMPARISON OF THE MEASUREMENT AND THE RESOLUTION-BROADENED THEORETICAL SPECTRUM INDICATES THAT THE COMPUTED RESOLUTION (OF 10 PERCENT AT 220 MEV) IS CORRECT. THE

EXCESS OF LOW-ENERGY EVENTS IS ATTRIBUTED TO DIRECT INTERACTIONS OF THE DEUTERONS WITH THE BERYLLIUM NUCLEUS.

740 MEV PROTONS ON A THICK URANIUM TARGET (SLIDES 4 AND 5)

NOW I WOULD LIKE TO PRESENT SOME MEASUREMENTS OF HIGH-ENERGY NEUTRON SPECTRA PRODUCED BY 740 MEV PROTON BOMBARDMENT OF A THICK URANIUM TARGET. THE NEXT SLIDE (#4) 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.

THE NEXT SLIDE (#5) SHOWS THE MEASURED SPECTRA AT 50 DEGREES AND 130 DEGREES (FROM 740-MEV PROTON BOMBARDMENT OF A 30 CM THICK URANIUM-238 TARGET.) THE ORDINATE IS THE DIFFERENTIAL NEUTRON YIELD (EXPRESSED IN NEUTRONS PER PROTON PER STERADIAN PER MEV.) THE ABSCISSA

IS THE NEUTRON ENERGY IN MEV. THE HISTOGRAMS REPRESENT THE CALCULATED SPECTRA.⁽⁴⁾ ONE OBJECTIVE OF THESE MEASUREMENTS WAS TO TEST THE VALIDITY OF THE PREDICTIONS OF THE MONTE CARLO CALCULATION BASED ON THE INTRANUCLEAR CASCADE MODEL; MORE SPECIFICALLY, THERE WAS A NEED TO TEST THE VALIDITY OF CALCULATIONS MADE FOR THE DEVELOPMENT OF AN INTENSE, PULSED, NEUTRON SOURCE AT THE LOS ALAMOS MESON PHYSICS FACILITY. BELOW 20 MEV, THE MEASUREMENTS ARE IN AGREEMENT WITH THE CALCULATIONS. AT 50 DEGREES, THE YIELD ABOVE 25 MEV IS 1.3 TIMES GREATER THAN CALCULATED; AT 130 DEGREES, THIS FACTOR INCREASES TO 1.6. FOR NEUTRONS ABOVE 25 MEV, THE YIELD AT 50 DEGREES IS 5 TIMES THAT AT 130 DEGREES.

PRINCIPLE OF THE FOUR-FOLD SPECTROMETER (SLIDE 6)

THE NEXT SLIDE (#6) SHOWS A MODIFIED VERSION OF THE SPECTROMETER WHICH WAS DEVELOPED TO EXTEND THE UPPER LIMIT OF THE SPECTROMETER TO ABOUT 1 GEV. IN THE MODIFIED VERSION, A COUNTER TELESCOPE (CONSISTING OF SCINTILLATION DETECTORS D3 AND D4) DETECTS THE RECOIL PROTON IN COINCIDENCE WITH THE SCATTERED NEUTRON. FOR

AN EVENT TO BE ACCEPTED, A FOUR-FOLD (D1-D2-D3-D4) COINCIDENCE IS REQUIRED WITHOUT A VETO FROM THE ANTICOINCIDENCE DETECTORS A1 AND A2. FOR NEUTRON-PROTON ELASTIC SCATTERING EVENTS, THE ANGLE PSI BETWEEN THE RECOIL PROTON AND THE SCATTERED NEUTRON IS 90 DEGREES FOR NON-RELATIVISTIC ENERGIES. FOR RELATIVISTIC ENERGIES, THE ANGLE PSI DECREASES SLOWLY WITH INCREASING ENERGY.

THIS FOUR-FOLD COINCIDENCE VERSION OF THE SPECTROMETER REDUCES THE BACKGROUND FROM CHANCE COINCIDENCES AND ALSO FROM COMPETING INELASTIC REACTIONS FROM CARBON AND HYDROGEN. BACKGROUND FROM INELASTIC NEUTRON-PROTON INTERACTIONS IS SMALL BECAUSE THESE EVENTS MUST SATISFY THE KINEMATIC AND THE COPLANARITY REQUIREMENTS FOR NEUTRON-PROTON ELASTIC SCATTERING. ALSO, IN THE REGION FROM 500 MEV TO 1 GEV, THE TOTAL CROSS SECTION FOR INELASTIC NEUTRON PROTON SCATTERING IS LESS THAN ONE-HALF OF THE TOTAL CROSS-SECTION FOR ELASTIC NEUTRON-PROTON SCATTERING. NEUTRONS SCATTERED QUASI-ELASTICALLY FROM PROTONS IN THE CARBON NUCLEUS CAN SATISFY THE FOUR-FOLD COINCIDENCE REQUIREMENT BECAUSE SUCH EVENTS ARE KINEMATICALLY SIMILAR TO ELASTIC NEUTRON-PROTON-

SCATTERING. EVEN THOUGH THE BACKGROUND FROM NEUTRON-CARBON INTERACTIONS IN THE FIRST SCINTILLATOR IS MUCH SMALLER IN THE FOUR-FOLD VERSION THAN IN THE TWO-FOLD VERSION OF THE SPECTROMETER, IT IS NECESSARY TO SUBTRACT THIS BACKGROUND BY MAKING SEPARATE MEASUREMENTS WITH D1 SCINTILLATORS THAT DIFFER IN THEIR RELATIVE HYDROGEN-CARBON COMPOSITION.

724 MEV PROTONS ON BERYLLIUM (SLIDE 7)

THE NEXT SLIDE (#7) SHOWS THE RESULTS OF A MEASUREMENT OF THE NEUTRON SPECTRUM AT 0 DEGREES FROM 724 MEV PROTONS ON A (1-INCH THICK) BERYLLIUM TARGET. THE ORDINATE IS THE RELATIVE NUMBER OF EVENTS PER MEV; THE ABSCISSA IS THE NEUTRON ENERGY IN MEV. THE SPECTRUM EXHIBITS PEAKS AT ABOUT 350 AND 700 MEV. THE HALF-WIDTH AT HALF-MAXIMUM OF THE HIGH-ENERGY PEAK INDICATES THAT THE ENERGY RESOLUTION AT 700 MEV IS ABOUT 16 PERCENT IN AGREEMENT WITH THE CALCULATED RESOLUTION OF 17 PERCENT. IN COMPARING OUR MEASUREMENT WITH THE PREVIOUS MEASUREMENT OF KISELEV⁽⁵⁾ AND HIS COLLABORATORS AT 680 MEV, THERE IS A DISCREPANCY IN THE POSITION OF THE QUASI-ELASTIC PEAK. IN THE RUSSIAN WORK, THE QUASI-ELASTIC PEAK IS AT ABOUT 50 MEV BELOW THE MEAN PROTON

BOMBARDING ENERGY; WHEREAS IN OUR MEASUREMENT, THE POSITION OF THE QUASI-ELASTIC PEAK AND THE MEAN PROTON BOMBARDING ENERGY AGREE (WITHIN EXPERIMENTAL ERROR). THE MAGNITUDE OF THE QUASI-ELASTIC PEAK IN THE TWO EXPERIMENTS APPEARS TO BE DIFFERENT, BUT THIS DIFFERENCE SEEMS TO BE DUE TO DIFFERENCES IN THE ENERGY RESOLUTION OF THE MEASUREMENTS. BERTINI⁽⁶⁾ AT THE OAK RIDGE NATIONAL LABORATORY IS CURRENTLY CARRYING OUT A MONTE CARLO INTRANUCLEAR CASCADE CALCULATION FOR COMPARISON WITH OUR DATA.

NEUTRON SPECTRUM AT 0° FROM 724 MEV PROTONS ON COPPER (SLIDE 8)

THE NEXT SLIDE (#8) SHOWS THE RESULTS OF A MEASUREMENT OF THE NEUTRON SPECTRUM AT 0 DEGREES FROM 724 MEV PROTONS ON A (1/4-INCH) COPPER TARGET. ALSO SHOWN IS THE NEUTRON SPECTRUM PREDICTED BY THE INTRANUCLEAR CASCADE MODEL FOR THE INTERVAL FROM 0 TO 1 DEGREE. FOR COMPARISON, THE MEASURED AND CALCULATED SPECTRA ABOVE 200 MEV WERE NORMALIZED TO AN ARBITRARY CROSS SECTION. THE ORDINATE IS THE RELATIVE CROSS SECTION IN MILLIBARNS PER STERADIAN PER MEV; THE ABSCISSA IS THE NEUTRON ENERGY IN MEV. THE COMPARISON BETWEEN THE CALCULATION AND THE MEASUREMENT IS POOR, PARTICULARLY IN THE REGION BELOW ABOUT 350 MEV. THE DATA INDICATE THAT THE

RELATIVE NUMBER OF NEUTRONS IN THE CONTINUUM BELOW ABOUT 350 MEV
IS MUCH GREATER THAN PREDICTED.

SUMMARY

THE EXPERIMENTAL RESULTS WHICH I HAVE PRESENTED TODAY
DEMONSTRATE THE PERFORMANCE OF THE SPECTROMETER IN THE ENERGY
REGION FROM 1 TO ABOUT 725 MEV. FURTHERMORE, IT APPEARS THAT
THE SPECTROMETER CAN BE USED FOR NEUTRON ENERGIES UP TO AT LEAST
1 GEV.

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FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8