Scattering of High Energy Neutrons by Protons with Non-Central Interaction

K. N. Hsu and T. M. Hu
University College, London, England
February 4, 1949

CALCULATIONS have been made by several authors[1–6] for the scattering of high energy neutrons by protons, using various forms of interactions. Bethe and Camac[1] have shown that with a purely central interaction of the spherical-well type, both the angular distribution and the total cross section for 80 Mev neutrons can be correctly predicted if the range is assumed to be 2.0×10^{-13} cm. Similar results have been reported by Barker[2] for an exponential-well type of potential with range 1.0×10^{-13} cm. If a non-central interaction of the spherical-well type is assumed, it is found that while the observed angular distribution can be approximately reproduced if a purely exchange interaction is used, the total cross section is much larger than the empirical value.[3,4] In these calculations, the range is assumed to be 2.8×10^{-13} cm. If the same range is used for both the tensor and the central part of the interaction, it is not possible to reduce the range much.[7] Furthermore, a detailed investigation with the Born's approximation by Burhop and Yadav[6] shows that due to the rapid increasing of the tensor interaction, reduction of the range may even cause the total cross section to increase. It seems desirable to try other types of radial variation of the interaction. In this work, we wish to report the results of similar calculations for 83 Mev neutrons with Yukawa and exponential-well type of interaction.

The potential for even states is assumed,

$$V_{\text{even}}(r)=-\{A+\tfrac{1}{2}B(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2-1)+CS_{12}\}\,V(r/r_0)$$

where, for Yukawa well,

$$V(r/r_0)=(r_0/r)e^{-r/r_0}$$
$$r_0=1.18\cdot10^{-13}\ \text{cm}$$
$$A=10.4\ \text{Mev},\quad B=-18.25\ \text{Mev},\quad C=79.6\ \text{Mev},$$

and for exponential well

$$V(r/r_0)=e^{-2r/r_0}$$
$$r_0=1.74\cdot10^{-13}\ \text{cm}$$
$$A=85\ \text{Mev},\quad B=6.26\ \text{Mev},\quad C=70\ \text{Mev}.$$

The ranges in both cases are consistent with the results of proton-proton scattering experiments. The constants for exponential well are those calculated by Massey and Hu[7] and those for Yukawa well are determined by one of us (K. N. Hsu).

For odd states, the potentials are fixed by the assumed exchange property of the interaction. We have studied the usual alternatives, namely, the exchange property is either similar to that predicted by the charged or the symmetrical meson theory. It is interesting to note that in the case of the Yukawa well of the assumed range, the charged theory will predict a stable $^3P_0$ state lower than the $^3S_1+^3D_1$ state, in direct contradiction to the experimental fact that the deuteron has spin unity. This case is still included in the calculation for the interest of comparison with other cases.

The results are given in Fig. 1 and Table I, together with the results for the spherical-well case obtained by Massey, Burhop, and Hu.[5] It is clear from the figure that angular distribution varies considerably with the shape of the potential well. From the preliminary reports of the measured angular distribution,[8] the Yukawa well with the symmetrical interaction fits the empirical results better than the other two shapes of interaction. The total cross section is not sensitive to the shape of the interaction provided a reasonable range is chosen for a given shape. The values given in the table are much larger than the empirical value for all shapes of well with exchange or symmetrical interaction.

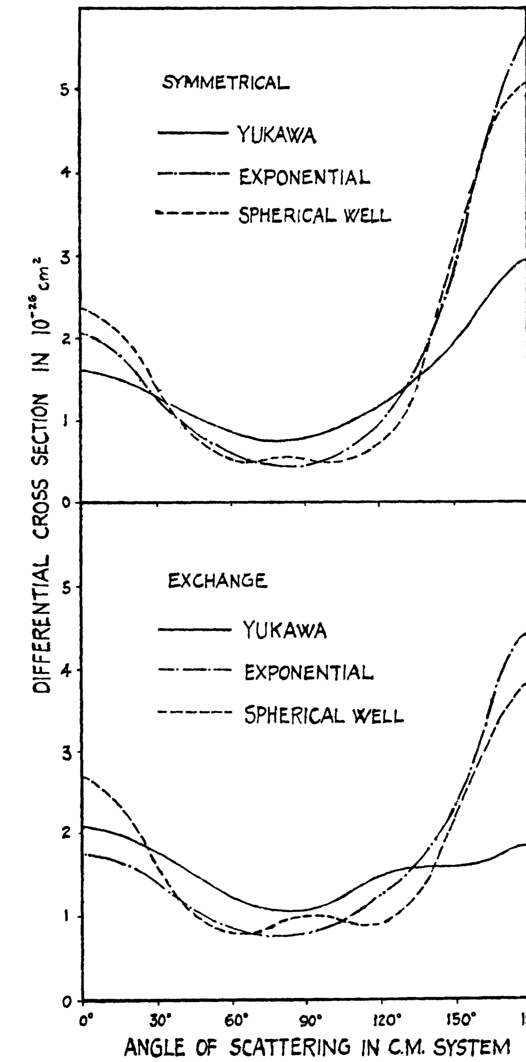

FIG. 1. Angular distribution of scattered neutrons.

One of the obvious ways to reduce the total cross section is to assume that the nucleons do not interact in odd states.* Total cross sections calculated under this assumption are given in the last column Table I. This assumption, however, will predict an angular distribution perfectly symmetrical with respect to the plane $\theta=\pi/2$, which does not seem to agree very well with the measured distribution.[8] Analysis of the proton-proton scattering experiments also indicates a repulsive interaction for ^3P states.[9]

Another possible modification is to assume different ranges for the central, tensor, and singlet interactions. This view is supported by the scattering experiments of thermal neutrons by para- and orthohydrogen molecules[10] and the coherent

TABLE I. Total cross section for 83 Mev neutrons in 10^{-26} cm^2.

	Symmetrical	Exchange	No interaction in odd states	Experiment (90 Mev)*
Yukawa	14	17	11	
Exponential	13	15	9.4	8.3 ±0.4
Spherical well	14	16	—	

* Cook, McMillan, Paterson and Sewell, Phys. Rev. 72, 1264 (1947).

scattering of neutrons by NaH crystals.[11] Investigations along this line are in progress in this department. A more detailed account of the present work may appear elsewhere.

It is our pleasure to thank Professor Massey and Dr. Burhop for their interest in this work. We are much indebted to Miss K. Blunt for solving the simultaneous differential equations necessary for the calculation of the phases of the coupled states. Thanks are due to Mr. Yadav for his assistance in the calculation of the angular distribution for the exponential-well case.

* This type of interaction was first suggested by Serber.

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Comparison of the Flow of Iostopically Pure Liquid He^3 and He^4

DARRELL W. OSBORNE, BERNARD WEINSTOCK, AND BERNARD M. ABRAHAM
Argonne National Laboratory, Chicago, Illinois
January 14, 1949

IN order to determine whether liquid He^3 has a transition to a superfluid state such as that exhibited by liquid He^4, the isothermal flow of isotopically pure liquid He^3 through a narrow channel or superleak has been studied from 3.02°K (0.18° below the normal boiling point[1,2]) to 1.05°K. The rate of flow of liquid He^3 was observed to decrease monotonically as the temperature was lowered. In contrast, the rate of flow of liquid He^4 through the same channel was observed to decrease as the temperature was lowered, until the lambda-point (2.19°K) was reached, and below this point the rate rose very sharply. The mass rate of flow of the two isotopes as a function of temperature is shown in Fig. 1. From these results it is clear that no superfluid transition occurs in He^3 down to 1.05°K.

The He^3 used in this experiment was obtained from the decay of tritium gas which had been initially freed from helium by passage through a palladium valve. After sufficient He^3 had grown in by decay, the bulk of the tritium was removed from it by means of a palladium valve, and the residual tritium was then removed by circulating the He^3 through a U-tube immersed in liquid helium. No He^4 was detected in a spectrographic analysis of the sample (kindly performed by Mr. J. K. Brody). The limit of detection was estimated to be 0.1 percent.

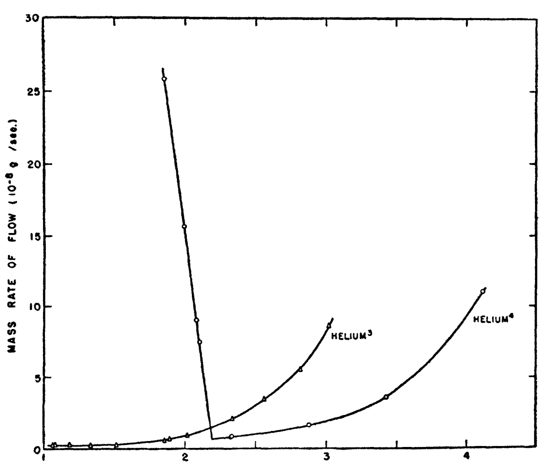

FIG. 1. Mass rate of flow of liquid He^3 and of liquid He^4 through a 7×10^{-5} cm annulus, as a function of temperature.

The experiment was similar to that which Giauque, Stout, and Barieau[3] performed to measure the viscosity of liquid He^4. The superleak was constructed by shrinking 0.05-cm i.d. Pyrex glass capillary around a platinum wire 0.013 cm in diameter and 5.5 cm long. On cooling, a narrow channel was formed due to the difference in the coefficients of expansion of the two materials. By measuring the rate of flow of He^4 gas through the leak at 4.22°K and at various pressures and by using the known viscosity[4] and virial coefficients[5] of He^4 gas, the width of the annulus was estimated to be 7×10^{-5} cm. The whole assembly was in the shape of long U-tube, which was supported vertically in the liquid helium cryostat, with the superleak near the bottom of one leg. The upper part of the superleak was connected to the filling system with 0.05-cm i.d. capillary. The other leg of the U-tube was expanded from 0.05-cm to 0.20-cm i.d. above the helium bath level and went to the measuring system. To make a measurement, liquid He^3 or He^4 was condensed on top of the leak until a liquid height of a few mm was observed. The material that flowed through the superleak expanded into an 1100-cc volume, and the rate at which the pressure developed was observed with a Pirani gauge. A mercury diffusion pump was used to exhaust the measuring system prior to each rate measurement. The exhaust gas from the diffusion pump was fed back to the filling system by means of a Toepler pump.

Other experimenters[6-10] have looked for superfluidity of He^3 by studying transport properties of dilute solutions of He^3 in He^4 at temperatures down to 1.5°K. However, as has been pointed out elsewhere,[6,11] the absence of a superfluid state of He^3 can be demonstrated only by studies of the pure liquid. The present experiment with the pure liquid has demonstrated that there is no superfluid transition in He^3 down to 1.05°K, but the question remains as to whether this temperature is sufficiently low. In this connection, it should be noted that the lambda-transition of He^4 occurs at 0.52 times the normal boiling point, and that the vapor pressure at the lambda-point is 38.3 mm; whereas in this experiment no lambda-transition was observed in He^3 down to a temperature which is 0.33 times the normal boiling point, where the vapor pressure is 11 mm.[2] In any case, the experimental results lend support to the hypothesis that the lambda-transition of He^4 is due to Boise-Einstein statistics.

The authors are indebted to Professor J. W. Stout of the Institute for the Study of Metals, University of Chicago, for many helpful discussions.

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Yields of Some Photo-Nuclear Reactions

M. L. PERLMAN*
Research Laboratory, General Electric Company, Schenectady, New York
February 7, 1949

IT has been shown that in the neighborhood of mass number 60 a transition occurs in the relative yield values for the