

These systematics were derived primarily from measured spallation excitation functions and  $(n, f)$  cross sections, using calculated values for the total compound-nucleus formation cross section. For the cases studied here, the agreement with the present measurements is reasonable. Our data on  $^{239}\text{Np}$  are also in qualitative agreement with the data of Boyce *et al.*<sup>4</sup>; however, determination of  $P_f$  or  $P_{\text{ER}}$  from their data also requires the use of calculated compound-nucleus cross sections in the analysis.

We note that in the region of second-chance fission  $P_{\text{ER}}$  is essentially constant. This is an indication that  $\Gamma_n/\Gamma_f$  for  $^{235,234}\text{Pa}$  and  $^{239,238}\text{Np}$  is not a strongly varying function of excitation energy. Using the average value for  $^{239}\text{Np}$  in the second-chance fission region,  $P_{\text{ER}} = 0.215$ , along with the measured value<sup>1</sup> of  $P_f = 0.50$  (with a 10% uncertainty) for 7 to 11 MeV excitation in  $^{238}\text{Np}$ , we obtain for  $^{239}\text{Np}$  alone values of  $P_f = 0.57 \pm 0.04$  and  $\Gamma_n/\Gamma_f = 0.75 \pm 0.13$ . The uncertainty in these values is dominated by the uncertainty of the previous  $P_f$  measurements. For comparison, the measured value of  $P_f$  for  $^{239}\text{Np}$  at 8 to 11 MeV excitation is  $0.41 \pm 0.04$ , giving  $\Gamma_n/\Gamma_f = 1.44 \pm 0.22$ .

In conclusion, we have shown that the measurement of evaporation-residue cross sections is a sensitive tool for the determination of  $\Gamma_n/\Gamma_f$  as a function of excitation energy. The technique is not subject to the large uncertainties inherent in determining  $\Gamma_n/\Gamma_f$  from direct-reaction fission-probability measurements for cases where  $P_f$  approaches 1, nor does it require the use of calcu-

lated total compound-nucleus cross sections needed to extract  $\Gamma_n/\Gamma_f$  from either spallation or total fission cross-section measurements. In the near future these measurements will be extended to a number of other cases and will be compared with the results of microscopic statistical model calculations.

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## $p$ - $^4\text{He}$ Elastic Scattering at 1.05 GeV\*

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The elastic differential cross section of 7.0-GeV/c  $^4\text{He}$  scattered from hydrogen (equivalent  $T_p = 1.05$  GeV) has been measured over a range  $0.17 \leq -t \leq 0.85$  (GeV/c)<sup>2</sup>. The experiment has very low background ( $\leq 2\%$ ), adequate  $t$  resolution ( $\leq 5\%$ ), a good absolute normalization (15%), and a statistical accuracy in the interference region of about 3%. The data show a shallow first minimum and a shape very similar to the recent data from Centres d'Etudes Nucléaires de Saclay.

We present here results which bear on the shape and magnitude of the  $p$ - $^4\text{He}$  elastic cross section in the region of the first interference min-

imum. Recent data<sup>1-7</sup> show significant variations in the depth of the first minimum as a function of energy. In particular, there is a striking differ-

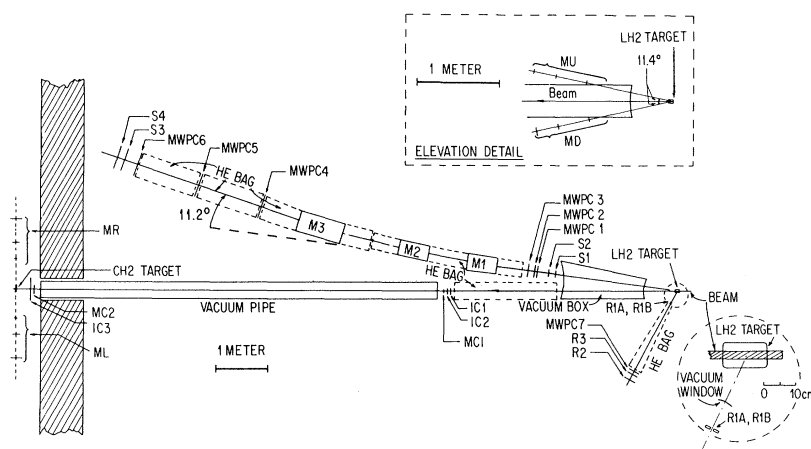


FIG. 1. Plan view of the experimental area. Symbols are explained in the text.

ence between the data of Palevsky *et al.*<sup>6</sup> at 1.0 GeV and those of the Centre d'Etudes Nucléaires de Saclay group at 1.05<sup>2</sup> and at 1.15 GeV.<sup>7</sup> This apparent discrepancy has led to speculation about possible theoretical<sup>8</sup> or experimental causes for the "filling in" of the dip. The data we present here confirm the existence of the shallow minimum at 1.05 GeV, and also provide both a good absolute normalization of the cross section and an accurate measurement of the scattering angle. These data, together with results from other energies, will be discussed more extensively in a later publication.

A plan view of the experiment is shown in Fig. 1.  $\alpha$  particles from the Berkeley Bevatron were spilled from the machine by resonant extraction into an evacuated beam transport system which delivered at the experimental area a beam spot 16 mm (horizontal) by 16 mm (vertical) with a divergence of 3.3 mrad (horizontal) by 4.0 mrad (vertical) (quoted dimensions are full width at half-maximum). The momentum of the beam at the target was  $6981 \pm 5$  MeV/c. This result was obtained from Bevatron operating conditions and agrees with our spectrometer measurements. The momentum spread in the beam was smaller than our spectrometer resolution and is estimated to be about 0.2%. Information on the position, size, and direction of the beam was obtained from two integrating wire chambers (MC1, MC2) which measured horizontal and vertical beam profiles for each spill. The incident flux was measured by three ion chambers and a pair of scintillation telescopes (MR, ML) viewing a target in the beam. No contamination of the beam was observed at the 1–2% level.

The liquid hydrogen was contained in a 5.1-cm-diam cylinder, 10.2 cm along the beam. The number of beam-target interactions was monitored by a pair of scintillation telescopes. For the target-full condition, the ratio of this monitor to the incident flux was constant ( $\sigma = 3\%$ ) over the duration of the experiment (the target-evacuated contribution to this ratio was only 9%).

The scattered  $\alpha$  particle was detected in a large, movable magnetic spectrometer consisting of scintillators (S1–S4), multiwire proportional chambers (MWPC1–MWPC6), and three dipole magnets. The spectrometer had a solid angle of 0.8 msr, and a momentum acceptance of  $\pm 10\%$ . Pulse-height and timing information from each scintillator were recorded in addition to the position data from the MWPC's. The spectrometer data provided an unambiguous mass identification of the  $\alpha$  particle, as well as its momentum ( $\sigma = 0.8\%$ ), scattering angles  $\theta, \varphi$  ( $\sigma = 0.1^\circ, 0.1^\circ$ ), and point of origin in the target. High chamber redundancy resulted in an overall spectrometer track efficiency of about 95%. The recoil proton was detected in a telescope consisting of a two-element hodoscope (R1A, R1B) which defined the target length and the geometric contribution to the angular resolution; a MWPC to measure the scattering angles; and two scintillators to provide pulse-height, timing, and range information. The recoil angles ( $\theta_p, \varphi_p$ ) were used to delimit the acceptance of the system; the simple geometry permits a straightforward calculation of the acceptance. The squared four-momentum transfer,  $t$ , for each event was calculated from  $\theta_p$ , which is readily susceptible to direct, absolute measurement, and which varies rapidly with

$t$ .

The calculated resolution  $\sigma_t$  varied almost linearly from  $0.009 \text{ (GeV/c)}^2$  at  $t = -0.17 \text{ (GeV/c)}^2$  (where it is dominated by multiple scattering in the target) to  $0.0145 \text{ (GeV/c)}^2$  at  $t = -0.85 \text{ (GeV/c)}^2$  (where it is given by the geometric resolution of the recoil detector). The calculated resolution is in good agreement with the measured distributions of opening angle and coplanarity.

Helium bags were used in the spectrometer and recoil telescope to reduce multiple scattering; and the beam, after passing through the target, was contained in vacuum or helium to minimize the number of background-producing interactions. The trigger requirement was a coincidence between the two spectrometer arms within a generous time window, thus permitting the final coincidence requirement to be imposed in the subsequent analysis, as well as providing a simultaneously collected sample of randoms. For each event the information from the scintillators and MWPC's were digitized in CAMAC modules and written onto magnetic tape by a computer which also provided on-line checks of the apparatus. After each machine spill, the spectrometer-magnet currents, the beam profiles, and numerous scalars were read and recorded on the tape, providing a spill-by-spill history of the experiment.

The constraints imposed by our measurements resulted in a very clean elastic signal, with typical background subtractions of about 1.5%. Successive angle settings were overlapped by about 50% so that the cross section at most values of  $t$  was measured in two different regions of the system acceptance. The  $\chi^2$  distribution for all repeated measurements was consistent with a normal curve of unit variance: No unexpected angle or setting dependences were found. An absolute calibration of the beam monitors was made using the  $^{11}\text{C}$  activation technique. (The required value of  $\sigma_{\text{tot}}$  for  $^{12}\text{C}(\alpha, X)^{11}\text{C}$  was measured in a separate experiment.) As a check of the overall absolute normalization of the experiment, the  $p$ - $p$  elastic cross section at 5.75 GeV/c was measured at three angle settings. A comparison of our results with other data at nearby energies is consistent with the value ( $\sigma = 15\%$ ) which we assign to the error in absolute normalization.

Our results for  $p$ - $^4\text{He}$  elastic scattering are shown in Fig. 2, where they are compared with the 1.05-GeV data from Centre d'Etudes Nucléaires de Saclay. In order to emphasize the excellent agreement in shape we have shifted each

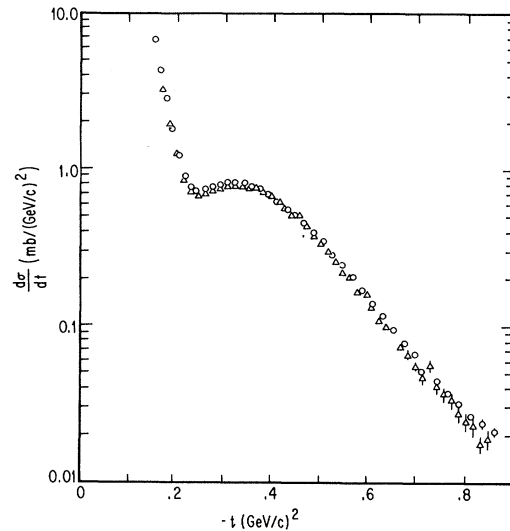


FIG. 2. The differential cross section at 1.05 GeV. The open circles are from Ref. 2; these data points have been shifted by  $-0.5^\circ$ . The triangles are the present work.

Saclay data point by  $-0.5^\circ$  in  $\theta_{\text{lab}}$  and recalculated  $t$  before plotting it. The need for such a shift becomes obvious if the data are plotted together versus the laboratory angle of the (equivalent) proton. No adjustment of the normalization has been made. Inspection of the data invites the following comments:

(1) *Adequacy of  $t$  resolution and the depth of the minimum.*—Considerable care was taken to minimize the amount of material and therefore the multiple scattering in the recoil arm. The primary sources of uncertainty were the beam divergence, the uncertainty in the location of the collimator aperture, and multiple scattering in the hydrogen. All sources contribute to an overall uncertainty ( $\sigma$ ) of less than  $0.01 \text{ (GeV/c)}^2$  in the region of the first minimum.

(2) *Accuracy of absolute laboratory angle measurement.*—The pulse-by-pulse monitoring of incident beam direction, the simplicity of the recoil angle measurement, and the cross checks provided by the redundant measurements lead us to conclude that the error in our absolute angle is no larger than  $0.15^\circ$ .

(3) *Error in absolute cross section.*—At our present stage of analysis we assign a conservative value of  $\sigma = 15\%$  to our overall absolute normalization error. We note that the original "relative normalization" of the Saclay data has turned out to be remarkably close to an absolute normalization.

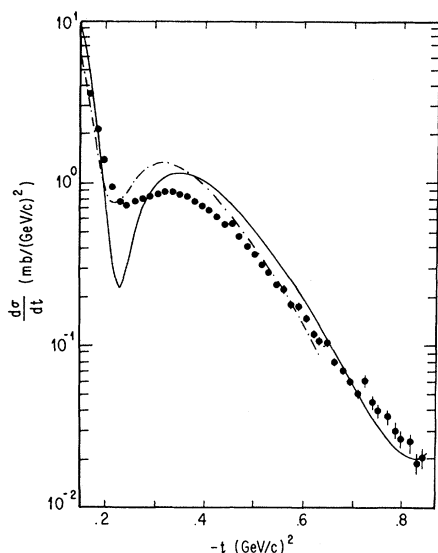


FIG. 3. Elastic scattering at 1.05 GeV. The dot-dashed (from Ref. 11) and solid curves are Glauber model calculations employing spin-dependent and spin-independent amplitudes, respectively. The data are from the present work.

In Fig. 3, we compare the measurement with two Glauber<sup>9</sup> model calculations. The first employs spin-independent, isospin-dependent nucleon-nucleon amplitudes

$$f_{pj}(t) = (i\sigma_{pj}/4\pi)(1 - i\alpha_{pj}) \exp(bt/2), \quad (1)$$

$$j = p, n;$$

and a form factor for helium fitted to the data of Frosch *et al.*<sup>10</sup> Parametric values for the total cross section  $\sigma_{pj}$ , for the ratio of real to imaginary parts  $\alpha_{pj}$ , and for the slope parameter  $\beta_{pj}$  are  $\sigma_{pp} = 47.5$  mb,  $\sigma_{pn} = 40.6$  mb,  $\alpha_{pp} = 0.1$ ,  $\alpha_{pn} = -0.2$ , and  $\beta_{pp} = \beta_{pn} = 5.75$  (GeV/c)<sup>2</sup>. The second Glauber model calculation, due to Auger, Gillespie, and Lombard,<sup>11</sup> employs spin-dependent, isospin-dependent amplitudes taken from recent analyses of nucleon-nucleon data. The parametric values of the spin-independent part are similar to those used in the calculation described above. As expected, the spin effects reduce some of the discrepancy with the data in the region of the first minimum.

As we have already remarked, the absolute

normalization of the present data can conservatively be considered to be reliable at the level of 15% ( $\sigma$ ). This accuracy is sufficient to establish that the absolute value of the cross section at the second maximum is considerably overestimated in most theoretical calculations using either the Glauber or the Kerman-McManus-Thaler<sup>12</sup> models. Corrections to the Glauber model do not significantly alter this conclusion,<sup>13,14</sup> and estimates of the effect of short-range correlations by Lambert and Feshbach<sup>15</sup> tend to increase the discrepancy with experiment in the region of the second maximum.

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