Coulomb Suppression Effects in the Proton-Proton Elastic Scattering Extracted from the ^{2}H$(p, pp)n$ Reaction

M. G. Pellegriti,[1,2] C. Spitaleri,[1,2] A. Musumarra,[1,2] L. Calabretta,[2]
S. Cherubini,[3,2] A. Di Pietro,[2] P. Figuera,[2] R. G. Pizzone,[2] S. Romano,[1,2]
S. Tudisco[1,2] and A. Tumino[1,2]

[1]*Dipartimento di Metodologie Chimiche e Fisiche per l'Ingegneria, Università di Catania, Italy*
[2]*Laboratori Nazionali del Sud, INFN, Catania, Italy*
[3]*Ruhr-Universität Bochum, Bochum, Germany*

The behaviour of the quasi-free *p*-*p* cross section is investigated in the framework of the Trojan Horse Method at relative enegies where the free *p*-*p* cross section is sensitive to the Coulomb interaction. For this reason the ^{2}H$(p, pp)n$ reaction was studied by using a proton beam energy of 6 MeV at Laboratori Nazionali del Sud, INFN, Catania. The experimental data have been compared with a simulation based on a Plane Wave Impulse Approximation approach.

§1. Introduction

The Trojan Horse Method (THM)$^{1)-12)}$ is an indirect method that allows two-body cross section measurements at energy far below the Coulomb barrier, starting from a three-body reaction.

It is possible to extract a two-body cross section ($a + b \to c + C$) from a measured three-body one ($a + A \to c + C + x$) where the chosen nucleus A has a high probability to be clusterized into $x \oplus b$ and x behaves as a spectator to the process (quasi-free mechanism). If the reaction energy is higher than the Coulomb barrier in the entrance channel of the three-body reaction, the two-body interaction can be considered as taking place inside the nuclear field.

Therefore, in this picture, the extracted two-body cross section refers to the nuclear interaction only, the Coulomb barrier being already overcome in the entrance channel.$^{4)}$

The present paper reports on the application of this method to the *p*-*p* scattering, the simplest case where the Coulomb suppression can be observed. The *p*-*p* cross section is well-known. Its energy trend is observed to be very similar to that of *n*-*n* or *p*-*n* systems ($\approx 1/v$) except at low proton energies where a deep minimum shows up ($E_{lab} = 382.43$ keV, $\theta_{cm} = 90°$) due to the interference between the nuclear and the Coulomb scattering amplitudes.$^{13)}$

So, if one extracts the *p*-*p* cross section, under the THM assumptions from a suitable three-body one, like the ^{2}H$(p, pp)n$ reaction, this extracted cross section is expected to show Coulomb suppression effects. For this reason, the ^{2}H$(p, pp)n$ reaction was studied at Laboratori Nazionali del Sud (LNS), INFN, Catania, at proton energy higher than the p+d Coulomb barrier and such that the *p*-*p* relative energy in the exit channel is in the region of the deep minimum.

Thus, the extracted results can be compared with the free *p*-*p* cross section containing all Coulomb effects as well as the *n*-*n* cross section that is sensitive to the nuclear interaction only.

§2. Experimental set-up

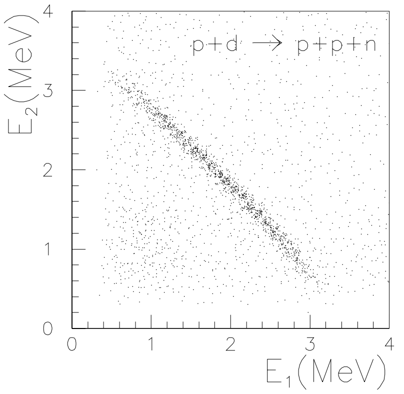

Fig. 1. The kinematic locus for the ^{2}H$(p,pp)n$ reaction at E_{beam}= 6 MeV; detectors are placed at $16.2° < \theta_{p1} < 24°$ and $15.6° < \theta_{p2} < 23.4°$.

A kinematically complete experiment was carried out at the LNS. The 15 MV Tandem provided a 6 MeV proton beam with a current of about 2 nA. The target consisted of a deuterated polyethylen film, 178 μg/cm^2 thick. Proton-proton coincidences were measured by two Position Sensitive Detectors (PSD) placed at roughly symmetrical angles with respect to the beam direction: $16.2° < \theta_{p1} < 24°$ and $15.6° < \theta_{p2} < 23.4°$. The *p*-*p* kinematic locus is shown in Fig. 1.

The energy and angular resolution of the PSD's were around 100 keV and 0.1°, respectively. A window was applied on the coincidence time spectra measured between the start and the stop signals given by the two detectors (see Fig. 2a)). Further selections were performed on the *p*-*p* kinematic locus and on the *q*-value spectra (Fig. 2b)). The investigated relative energy ranges from 0.3 to 0.8 MeV while the *p*-*p* center-of mass ranges from 30° to 150° (see Fig. 3).

§3. PWIA approach

The ^{2}H$(p,pp)n$ three-body reaction has been widely investigated (see, e.g., Refs. 16) and 17)).

The quasi-free mechanism for this reaction was studied at a beam energy of 145 MeV in Ref. 14) and at lower energies, ranging from 4.5 to 13 MeV, in Ref. 15). In these papers the Plane Wave Impulse Approximation (PWIA) was used in order to reproduce the data.

The 3-body cross section can be written, in PWIA, as

$$\begin{aligned}\frac{d^3\sigma}{d\omega_1 d\omega_2 dE_1} &= \frac{4(2)^{1/2}}{\pi^2}\frac{1}{{E_0}^{1/2}} \\ &\quad\times\frac{E_2{E_1}^{1/2}}{2{E_2}^{1/2}-{E_0}^{1/2}\cos\theta_2+E_1\cos(\theta_1-\theta_2)} \\ &\quad\times\frac{{E_\alpha}^{1/2}{E_\beta}^{1/2}\left({E_\alpha}^{1/2}+{E_\beta}^{1/2}\right)^3}{(E_\alpha+2E_3)^2(E_\beta+2E_3)^2}\cdot\frac{d\sigma}{d\omega}(\theta_{12},E_{12})\bigg|_{2\text{-}body}^{cm}. \qquad (3{\cdot}1)\end{aligned}$$

In Eq. (3·1), E_0 is the proton bombarding energy; E_1, E_2, θ_1 and θ_2 are the energies and the angles of the detected protons; E_3 is the energy of the third particle; E_α=2.225 MeV and E_β=59.8 MeV are the Hulthén function parameters; θ_{12}, E_{12} are the relative angle and energy of the two detected protons in the exit channel. If one neglects the off-energy shell effects the two-body cross section in Eq. (3·1) can be expressed through the free *p*-*p* scattering cross section.

The PWIA approach was used for the application of the THM in Refs. 2)–5). By measuring the three-body cross section, it is possible to extract the *p*-*p* two-body cross section term from Eq. (3·1).

In order to show the "Coulomb suppression", it is possible to compare the 3-body experimental data with a Monte Carlo simulation based on Eq. (3·1) where the measured 2-body cross section can be included. Equivalently one can compare the extracted 2-body cross section with the measured 2-body one. These two procedures will be followed by using both the free *p*-*p* and *n*-*n* cross sections for the comparisons.

The *first simulation* was done by using the free *p*-*p* cross section[18)] where the l=0 phase shift is calculated in the Jackson and Blatt formalism[19)] by using the Foldy et al. parameters:[20)] $-R/a = 3.704$ and $r_o = 2.76$ fm where a is the scattering length, r_o is the effective range, and R is equal to $\frac{\hbar^2}{me^2}$.

The total coincidence yield (in a.u., dots) of the experimental 3-body cross section corresponding to the region of Fig. 1 is shown in Fig. 4 as a function of proton energy a), proton-proton center-of-mass angle b) and proton-proton relative energy c).

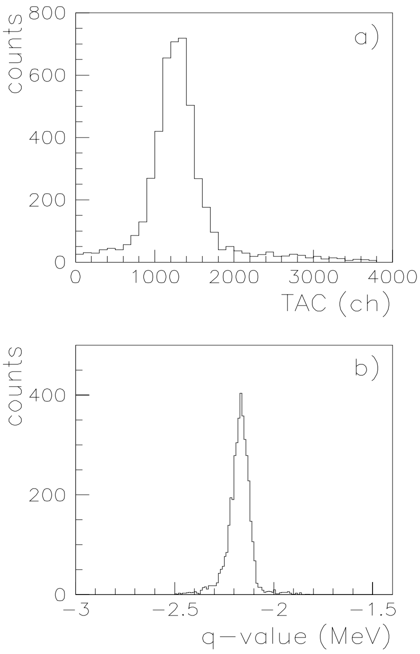

Fig. 2. a) Time spectra (TAC) measured between the start and the stop signals given by the two detectors after the kinematic selection in the E_1-E_2 spectra (see Fig. 1); b) q-value spectra for the ^{2}H$(p,pp)n$ reaction after a selection on the TAC spectra.

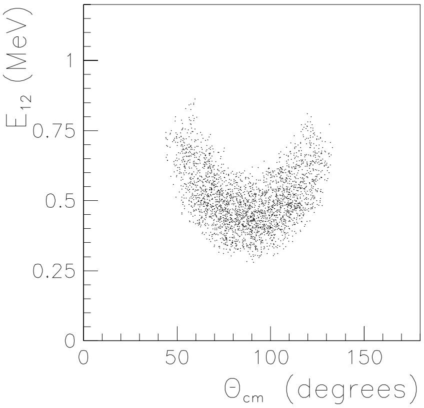

Fig. 3. Proton-proton relative energy E_{12} versus the center-of-mass angle θ_{cm}. The matrix is symmetric with respect to 90° because of the symmetric detection angles.

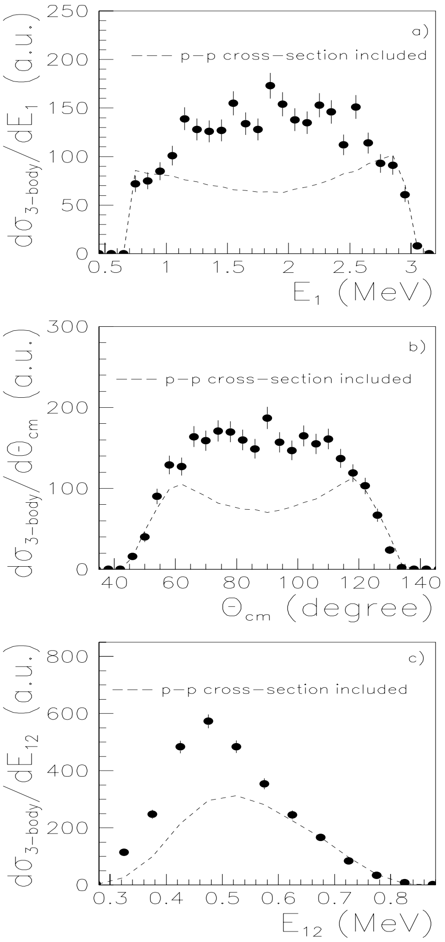

Fig. 4. Three-body cross section (in arbitrary units) for proton-proton coincidences as a function of a) the proton energy E_1, b) the two-body centre-of-mass θ_{cm}, and c) the two-body relative energy E_{12}. Dots represents experimental data while the dashed line is a calculation based on the spectator model where the two-body cross section (Eq. (3·1)) is the free proton-proton cross section.

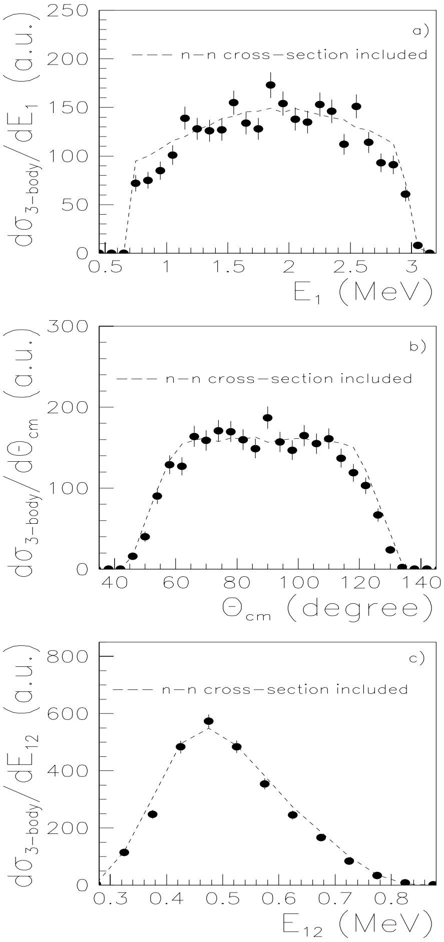

Fig. 5. The data of the three-body cross section (dots) for proton-proton coincidences are compared with a calculation (dashed curves) based on the spectator model where the modulation of the two-body cross section is given by the neutron-neutron cross section: the results are shown as a function of a) proton energy E_1, b) two-body centre-of-mass angle θ_{cm}, and the c) two-body relative energy E_{12}.

As expected, the calculation (dashed curves) does not reproduce the data. The two-body cross section was also extracted by dividing the measured three-body cross section by the phase space factor and the momentum distribution of the neutron inside the deuteron. The resulting cross section is shown in Fig. 6 as a function of the proton-proton relative energy. For each energy E_{12} the contribution of the different center-of-mass angles is summed up (see Fig. 3). As discussed above, the experimental data are compared with the free p-p cross section at the same relative

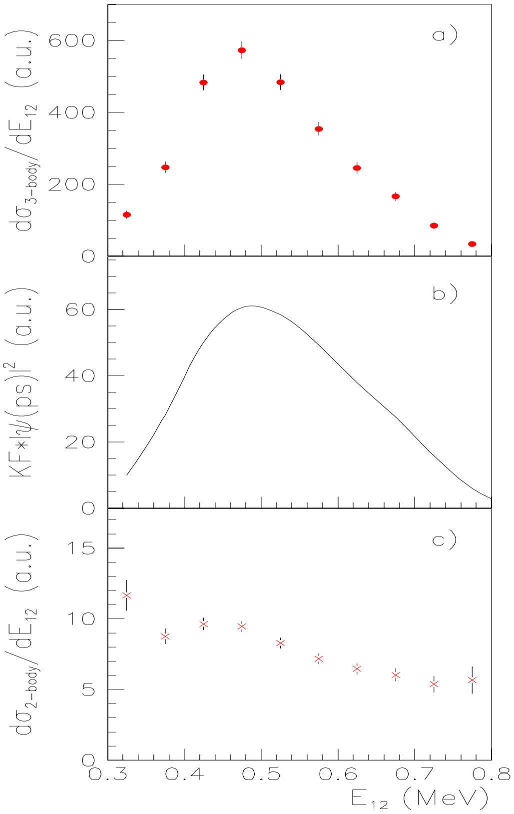

Fig. 6. This figure shows how the two body cross section is extracted from the three-body one; the experimental three-body cross section, the calculation of the kinematical factor mutiplied by the momentum distribution and the division between them are plotted as a function of E_{12} respectively in a), b), c). The spectra are in arbitrary units.

energy and angular ranges. The free *p*-*p* cross section and the extracted 2-body cross section are normalized with each other under the hypothesis that at relative energies above the proton-proton Coulomb barrier ($\approx$ 550 keV), they must be in agreement within experimental errors (Fig. 7a)). For this normalization, the disagreement between data and the free *p*-*p* cross section at lower energies is again evident.

The *second simulation* was done under the assumption that the Coulomb part is suppressed, so the neutron-neutron cross section replaced the free proton-proton cross section. This allows us to simply suppress all the Coulomb effects in the calculation.

The *n*-*n* cross section has been expressed by using the *effective-range theory* where the scattering length and the effective range ($a = -16.6$ fm, $r_o = 2.9$ fm) are from.[21] Now only the nuclear part of the interaction is taken into account in the simulation and the agreement for the 3-body cross section is fairly good (Figs. 5 a),b),c)). As in the previous case, the extracted two-body cross section has been also compared with the *n*-*n* cross section (Fig. 7b)). The normalization has been done

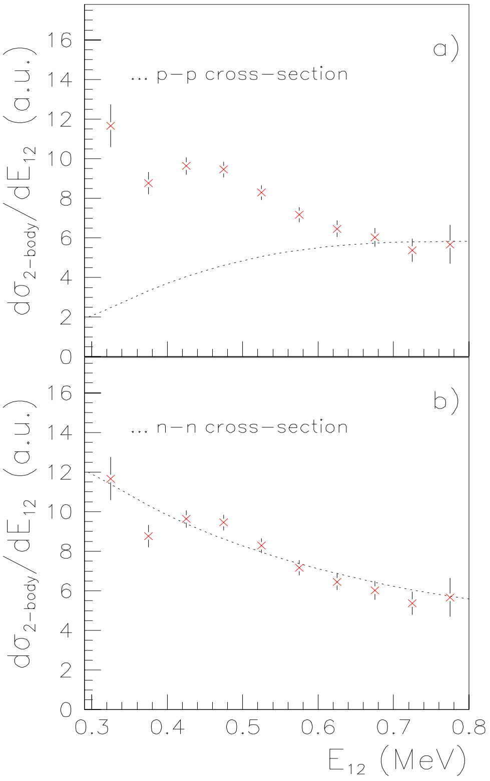

Fig. 7. The two-body cross section (stars) extracted in Fig. 6 is compared with the proton-proton cross section (dotted line) in a) and the neutron-neutron (dotted line) cross section in b).

at higher energies and again the cross section is plotted in arbitrary units. Here the agreement between data and n-n cross section is fairly good.

A calculation was done which accounts for the Final State Interaction between the neutron and the protons. The effect in the spectra considered is that of enhancing the value of the cross section close to the experimental proton energy thresholds both for the p-p and the n-n case.

§4. Conclusions

In this paper, the extracted p-p cross section has been compared first with the free p-p cross section (which includes all Coulomb effects) and then with the n-n cross section (which contains just the nuclear effects). We have observed that the Coulomb interaction is suppressed for this THM extracted cross section, it is a mainly nuclear cross section since it is in agreement with the n-n one.

These results, that confirms the THM predictions, represent an important starting-point for further investigations both on the experimental side (e.g. the absolute values of the cross section) and the theoretical one (e.g. detailed analysis from a microscopic point of view or in the framework of direct reactions).

Acknowledgements

We are grateful to A. Kiewsky, S. Rosati, M. Viviani, D. Miljanić, M. Lattuada and G. Baur for fruitful discussions. We thank the LNS Tandem staff for the support during the experiment.

References

1) G. Baur, Phys. Lett. B **178** (1986), 35.
2) S. Cherubini, V. N. Kondratyev, M. Lattuada, C. Spitaleri, D. Miljanić, M. Zadro and G. Baur, Astrophys. J. **457** (1996), 855.
3) G. Calvi, S. Cherubini, M. Lattuada, S. Romano, C. Spitaleri, M. Aliotta, G. Rizzari, M. Sciuto, R. A. Zappalà, V. N. Kondratyev, D. Milianiĉ, M. Zadro, G. Baur, O. Yu. Goryunov and A. A. Shvedov, Nucl. Phys. A **621** (1997), 139c.
4) C. Spitaleri, M. Aliotta, S. Cherubini, M. Lattuada, D. Miljanić, S. Romano, N. Soić, M. Zadro and R. A. Zappalà, Phys. Rev. C **60** (1999), 055802.
5) C. Spitaleri, M. Aliotta, M. Lattuada, R. G. Pizzone, S. Romano, A. Tumino, C. Rolfs, L. Gialanella, F. Strieder, S. Cherubini, A. Musumarra, D. Miljanic, S. Typel and H. H. Wolter, Eur. Phys. J. **15** (2000), 181.
6) C. Spitaleri, S. Typel, R. G. Pizzone, M. Aliotta, S. Blagus, M. Bogovac, S. Cherubini, P. Figuera, M. Lattuada, M. Milin, D. Milianiĉ, A. Musumarra, M. G. Pellegriti, D. Rendic, C. Rolfs, S. Romano, N. Soic, A. Tumino, H. H. Wolter and M. Zadro, Phys. Rev. C **63** (2001), 055801.
7) M. Lattuada, R. G. Pizzone, S. Typel, P. Figuera, D. Milianiĉ, S. Cherubini, A. Musumarra, M. G. Pellegriti, D. Rendic, C. Rolfs, S. Romano, N. Soic, A. Tumino, C. Spitaleri, H. H. Wolter and M. Zadro, Astrophys. J. **562** (2001), 1076.
8) A. Musumarra, R. G. Pizzone, S. Blagus, M. Bogovac, P. Figuera, M. Lattuada, M. Milin, D. Milianiĉ, M. G. Pellegriti, D. Rendic, C. Rolfs, N. Soic, C. Spitaleri, S. Typel, H. H. Wolter and M. Zadro, Phys. Rev. C **64** (2001), 068801.
9) C. Spitaleri, S. Cherubini, A. Del Zoppo, A. Di Pietro, P. Figuera, M. Gulino, M. Lattuada, D. Milianiĉ, A. Musumarra, M. G. Pellegriti, R. G. Pizzone, C. Rolfs, S. Romano, S. Tudisco and A. Tumino, Nucl. Phys. A **719** (2003), 99.
10) A. Tumino, C. Spitaleri, A. Di Pietro, P. Figuera, M. Lattuada, A. Musumarra, M. G. Pellegriti, R. G. Pizzone, C. Rolfs, S. Romano, S. Tudisco and S. Typel, Phys. Rev. C **67** (2003), 065803.
11) S. Typel and H. H. Wolter, Few-Body Systems **29** (2000), 7.
12) S. Typel and G. Baur, Ann. of Phys. **305** (2003), 228.
13) J. E. Brolley, J. D. Seagrave and J. G. Beery, Phys. Rev. **135** (1964), B1119.
14) A. F. Kuches, Richard Wilson and Paul F. Cooper, Ann. of Phys. **15** (1961), 193.
15) V. Valković, D. Rendić, V. A. Otte, W. von Witsch and G. C. Phillips, Nucl. Phys. A **166** (1971), 547.
16) W. Glöckle, H. Witala, D. Hüber, H. Kamada and J. Golak, Phys. Rep. **274** (1996), 107.
17) A. Kievsky, C. R. Brune and M. Viviani, Phys. Lett. B **480** (2000), 250.
18) R. D. Evans, *The Atomic Nucleus* (McGraw-Hill Book Company, 1955).
19) J. D. Jackson and J. M. Blatt, Rev. Mod. Phys. **22** (1950), 77.
20) L. L. Foldy and E. Eriksen, Phys. Rev. **98** (1955), 775.
21) R. J. Slobodrian, Rep. Prog. Phys. **34** (1971), 175.