LAWRENCE LIVERMORE NATIONAL LABORATORY

LLNL-JRNL-489019

First measurements of the differential cross sections for the elastic n-3H and n-2H scattering at 14.1 MeV using an Inertial Confinement Fusion (ICF) facility

J. A. Frenje, C. K. Li, F. H. Seguin, D. T. Casey, R. D. Petrasso, D. P. McNabb, P. Navratil, S. Quaglioni, T. C. Sangster, V. Y. Glebov, D. D. Meyerhofer

June 20, 2011

Physical Review Letters

Disclaimer

First measurements of the differential cross sections for the elastic n-^{3}H and n-^{2}H scattering at 14.1 MeV using an Inertial Confinement Fusion (ICF) facility

J.A. Frenje, C.K. Li, F.H. Seguin, D.T. Casey and R.D. Petrasso[†]

Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

D.P. McNabb, P. Navratil and S. Quaglioni

Lawrence Livermore National Laboratory, California, 94550

T.C. Sangster, V. Yu Glebov and D.D. Meyerhofer[*]

Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623

For the first time the differential cross sections for the elastic neutron-triton (n-^{3}H) and neutron-deuteron (n-^{2}H) scattering at 14.1 MeV have been measured using an Inertial Confinement Fusion (ICF) facility. In these experiments, which were carried out by simultaneously measuring elastically scattered ^{3}H and ^{2}H ions from a deuterium-tritium ICF implosion at OMEGA laser, the differential cross section for the elastic n-^{3}H scattering was obtained with a higher accuracy than achieved in previous accelerator experiments reported in the literature. The experimental results obtained at central-mass (CM) angles ranging from 59° to 172° compare well with precision measurements of the isobaric analogue p+^{3}He reaction when isospin differences are accounted for via calculations that combine the resonating-group method with an *ab-initio* no-core shell model. Considering the uncertainties, these results experimentally demonstrate that recent advances in *ab-initio* theory of light-ion reactions can provide an accurate description of light-ion reactions.

PACS numbers: 52.57.-z, 25.40.Dn, 25.85.Ec, 25.45.-z, 29.30.Ep, 03.65.Nk, 27.10.+h, , 27.10.+h

The development of an accurate description of light-ion reactions is currently of great interest as that would provide valuable insights into low-energy nuclear reactions important to nuclear astrophysics. Radiative capture reactions, for example, occur in red giants at temperatures low enough that the reaction rates are too small to be directly measured in a laboratory. Extrapolation from measurements at higher energies is also suspect without a fundamental theory for computing these reactions. Fusion energy research also requires accurate cross sections for light-ion reactions to constrain models of inertial confinement fusion (ICF) experiments involving deuterium-tritium fuel. For instance, uncertainties in the differential cross section for the elastic n-^{3}H scattering need to be less than ~5% to reliably infer a fuel areal density (ρR) from the yield ratio between scattered neutrons and primary 14.1-MeV neutrons, called down-scatter ratio (*dsr*) [1], produced in an ICF implosion. The determination of the ρR from the *dsr* value is essential for understanding how the fuel is assembled in an implosion, and for ultimately guiding the community towards the demonstration of thermonuclear ignition and net energy gain [2] at the National Ignition Facility (NIF) [3].

Since the 1950's, the differential cross section for the elastic n-^{3}H scattering at 14.1 MeV has been subject to extensive experimental and theoretical studies. Kootsey *et al.* [4] measured the cross section at central-mass (CM) angles ranging from 55° to 165°, resulting in data with statistical uncertainties of ~20% and a systematic uncertainty of 11%. Shirato *et al.* [5] and Debertin *et al.* [6] measured the cross section in the CM angular range 100°-175° with an uncertainty varying from ~10% to ~70%, and their results are in good agreement with each other, but a factor of two smaller than the Kootsey data. Optical model calculations conducted by DeVries *et al.* [7] and by Sherif and Podmore [8] reproduced the Shirato and Debertin data in this CM angular range. Additionally, G.H Hale *et al.* [9] conducted an R-matrix analysis of all experimental data sets, and the result from that analysis forms the basis of current ENDF/B-VII evaluation of the differential cross section for the elastic n-^{3}H scattering that can be found in nuclear data bases. Although numerous efforts have been made to quantify this fundamental cross section, significant discrepancies exist between the different measurements and between measurements and models. However, a theoretical understanding of the n+^{3}H scattering based on first principles calculations is within reach [10]. For example, *ab initio* variational calculations using a hyper-spherical harmonics basis expansion performed with a modern nuclear Hamiltonian consisting of an accurate nucleon-nucleon potential and a three-nucleon interaction provide a good description of the elastic n+^{3}H scattering at low energies [11]. However, this type of calculation is currently limited to energies below the breakup threshold.

This letter describes the first measurement of the differential cross section for the elastic n-^{3}H scattering at 14.1 MeV using an ICF facility. It also describes a theoretical calculation of this cross section, which combines the resonating-group method (RGM) with an *ab-initio* no-core shell model (NCSM) [12]. Using this theoretical approach, an accurate assessment of the n-^{3}H cross section can be made from precision data taken for the isobaric analogue p-^{3}He reaction. In these experiments, which were carried out on the OMEGA laser [13], deuterium-tritium-gas-filled thin-glass capsules were imploded with a 30 kJ 1-ns square laser pulse. Each capsule, made of SiO_2, had a nominal diameter of 850 μm, a nominal gas-fill pressure of 20 atm, and a shell thickness of 3.5 μm. The fuel mixture at shot time was 48.2% ± 0.3% deuterium, 48.8% ± 0.3% tritium, 2.5% hydrogen and 0.5% helium-3 from the tritium decay. Under these conditions, the glass shell was entirely ablated when the deuterium-tritium reactions occurred. Each implosion, which acts as both a 14.1-MeV neutron source and deuterium-tritium target, produced a burn-averaged ion temperature of 8.5 ± 0.5 keV and neutron yield of about 4×10^{13}, which were measured with a neutron time-of-flight diagnostic [14]. The energy spectra of the emitted tritons and deuterons, elastically scattered by the 14.1-MeV neutrons, were measured simultaneously using a magnet-based charged-particle spectrometer (CPS) [15] installed on the OMEGA-target chamber (Fig. 1). One piece of CR-39 was fielded in the CPS for the simultaneous measurements of the scattered deuterons (d’) and tritons (t’) with energies greater than ~3.7 MeV and ~2.5 MeV, respectively. A measurement of DD-proton spectrum was conducted as well to check that the emitted charged particles were not subject to any significant plasma-energy losses [16].

d’ and t’ spectra measured simultaneously on three different OMEGA shots are shown in Figs. 2a-c. These spectra, which have been background subtracted, were obtained by putting constraints on the diameter and darkness of the observed ion tracks in the CR-39 (the triton, deuteron and background tracks have different characteristics that were used for the differentiation [15]). The remaining background that could not be rejected was characterized from regions on the CR-39 where d’ and t’ signal cannot be detected. The error bars shown in the spectra are statistical uncertainties associated with the number of signal and background counts in each energy bin. The DD-proton spectrum measured for shot 31753 (Fig. 2d) displays an average energy that is similar to the birth energy of 3.05 MeV (temperature corrected), indicating that energy losses are negligible. From the measured d' and t' spectra, the differential cross section for the elastic n-^{3}H and n-^{2}H scattering was determined by deconvolving the CPS-spectrometer response [17] and the Doppler broadened 14.1-MeV-neutron spectrum [18]. In the determination of the n-^{2}H cross section, the effect of the deuterons from the t(n,2n)d reaction was considered and accounted for. Here, it was assumed that the cross section for this reaction is 6 ± 4 mb, which covers the reported value in ref. [19], or about 3% ± 2% of the total deuteron spectrum in the range 3.7-7.3 MeV. Additionally, as the plasma had a burn-averaged ion temperature of 8.5 keV, a density of ~1 g/cm^3, and a total areal density of ~2-3 mg/cm^2, energy-loss effects were insignificant and thus not considered. From an energy-loss point of view, these plasma conditions correspond to a cold target with an areal density less than 0.3 mg/cm^2.

Fig. 3a and 3b show the differential cross sections for the elastic n-^{2}H and n-^{3}H scattering measured in this work. These cross sections, which are compared to the other data sets, are averages of the three measurements shown in Fig. 2a-c. The n-^{2}H cross section determined for each shot was normalized to a Fadeev calculation that is accurate to about 1% [20] and that normalization factor, modified by the deuterium-tritium fuel ratio, was subsequently applied to the measured n-^{3}H cross section for the same shot. As illustrated by Fig. 3a, the angular variation of the measured n-^{2}H elastic cross section is in good agreement with the Fadeev calculated cross section, indicating that the background subtraction, characterization of the response function, and the effect of the Doppler broadening are accurate, and that the deconvolution process provides high-fidelity data. The uncertainties shown for the n-^{3}H cross section (shown in Fig. 3b and Table 1) are based on the statistical uncertainty and the uncertainty associated with the normalization factor. As the total n-^{2}H elastic cross section and the deuterium-tritium-fuel ratio in these experiments has an uncertainty of 1.0% and 0.9%, respectively, the uncertainty in the normalization factor is estimated to be 1.4%. This results in a total uncertainty ranging from 4% to 7% in the CM-angle range of 60°-80°, which is the most important range for diagnosing ICF implosions over which the n-^{3}H cross section dominates the other ICF-relevant cross sections. This uncertainty should be contrasted to the total uncertainty larger than 20% for the Kootsey data, which is the only other data set in this angular range. Considering the uncertainties involved, the experimentally determined n-^{3}H cross section compares well with the current ENDF/B-VII evaluated cross section, which is based on Hale's R-matrix analysis of accurate *p*-^{3}He data in a wide range of energies. The fit parameters obtained in that analysis were then adjusted to account for the Coulomb effects, as explained in Ref. [9], and subsequently applied to the n-^{3}H reaction. The results from the R-matrix analysis are shown by the red-dashed line in Fig. 3b. Another theoretical approach, described in detail in Ref. [21], was recently developed for evaluating the cross section of light-ion reactions. This approach combines the *ab initio* no-core shell model with the resonating group method (NCSM/RGM), and unlike earlier *ab initio* approaches, it allows calculations of various nucleon-nucleus scattering processes for systems with $A > 4$, i.e., both on *s*- and *p*-shell nuclei [12,21]. The NCSM/RGM calculations were performed for the n-^{3}H and p-^{3}He systems using a realistic nucleon-nucleon interaction that includes Coulomb and other isospin breaking terms. From accurate p-^{3}He data, a correction factor (<15%) at forward angles was deduced and applied to the n-^{3}H calculation. The result from this evaluation is illustrated by the blue solid line in Fig. 3b, which is also in good agreement with our experimental data, but differs from the R-matrix analysis by a couple percent in the backward scattering angles of the outgoing neutron. Considering the estimated uncertainty of ~5% for the NCSM/RGM calculation, this discrepancy is however not significant. Additional details of the n-^{3}H and p-^{3}He NCSM/RGM calculations are found in Ref. [13].

In summary, we report on the first measurements of the differential cross section for the elastic n-^{3}H and n-^{2}H scattering at 14.1 MeV using an ICF facility. The resulting n-^{3}H data are of higher quality than achieved in previous accelerator experiments reported in the literature, and accurate enough to reliably determine the fuel ρR from the yield ratio between scattered neutrons and primary 14.1-MeV neutrons produced in an ICF implosion. The experimental results obtained at central-mass (CM) angles ranging from 59° to 172° are in good agreement with a theory that is based on isospin corrected *ab-initio* calculations of the isobaric analogue p+^{3}He reaction. Both measured and calculated cross sections compare well with current ENDF/B-VII evaluated cross section, which is based on Hale's R-matrix analysis. A total n-^{3}H elastic cross section of 941±47 mb was calculated using the NCSM/RGM method.

The authors would like to thank Prof. Dr. Evgeny Epelbaum for providing Fadeev calculations of n-^{2}H scattering at 14.1 MeV, which provided the basis for normalizing these experimental results. The work described here was supported in part by US DOE (Grant No. DE-FG03-03SF22691), LLE (No.412160-001G), LLNL (DE-AC52-07NA27344 and No.B504974), and GA under DOE (DE-AC52-06NA27279).

† Also Senior Research Scientist at Laboratory for Laser Energetic, University of Rochester.

* Also Department of Mechanical Engineering, and Physics and Astronomy, University of Rochester.

[1] J.A. Frenje *et al*., Phys. Plasmas **17**, 056311 (2010).

[2] B.K. Spears *et al*., "Prediction of ignition implosion performance using measurements of low-deuterium surrogates", to be submitted to Phys. Plasmas (2010).

[3] G.H. Miller *et al*, Nucl. Fusion **44**, S228 (2004).

[4] J. M. Kootsey, Nucl. Phys. **A113**, 65 (1968).

[5] S. Shirato *et al*., Nucl. Phys. **A267**, 157 (1976).

[6] W. Debertin et al., (1967). EXFOR data base, National Nuclear Data Center, Brookhaven.

[7] R. M. DeVries *et al*., Nucl. Phys. **A188**, 449 (1972).

[8] H. S. Sherif and B. S. Podmore, "Few particle problems in nuclear interaction", edited by I. Slaus *et al*. (North-Holland, Amsterdam, 1972) p. 691.

[9] G.H. Hale *et al.*, Phys. Rev. C **42**, 438 (1990).

[10] R. Lazauskas *et al.*, Phys. Rev. C **71,** 034004 (2005).

[11] M. Viviani *et al.*, Few Body Syst. **45**, 119 (2009).

[12] P. Navrátil, *et al.*, Proceedings of the INPC 2010 conference; arXiv:1009.3965[nucl-th]; P. Navratil, S. Quaglioni, J.D. Anderson, F.S. Dietrich, D.P. McNabb, and G.H. Hale, "Evaluation of the n + 3H Cross Section at E_n = 14 MeV," Lawrence Livermore National Laboratory Report LLNL-TR-423504 (2010).

[13] T.R. Boehly *et al*., Opt. Commun. **133**, 495 (1997).

[14] V.Yu Glebov *et al.*, Rev. Sci. Instrum. **75**, 3559 (2004).

[15] F.H. Séguin *et al*., Rev. Sci. Instrum. **74**, 975 (2003).

[16] D.G. Hicks *et al.*, Phys. Plasmas **7**, 5106 (2000).

[17] The CPS-spectrometer response is described by a 300 and 1000 keV rectangular distribution at 5 and 10 MeV, respectively. For a 8.5-keV plasma the Doppler broadened DT-neutron spectrum is described by a Gaussian distribution with a width of 520 keV (FWHM) [18].

[18] H. Brysk, Plasma Phys. **15**, 611 (1973).

[19] I.J. Thompson, Computer Physics Reports **7**, 167 (1988).

[20] E. Epelbaum *et al.*, Phys. Rev. C **66**, 064001 (2002).

[21] S. Quaglioni and P. Navratil, Phys. Rev. Lett. **101**, 092501 (2008); Phys. Rev. C **79**, 044606 (2009).

FIG. 1 (color). (a) The charged-particle spectrometer (CPS) [14] on OMEGA for simultaneous measurements of deuterons (d' > 3.7 MeV) and tritons (t' > 2.5 MeV) elastically scattered by 14.1-MeV neutrons in a deuterium-tritium-gas-filled thin-glass capsule implosion. A bending magnet (grey) was used for momentum analysis and a piece of CR-39 was used for detection of the scattered tritons and deuterons. A measurement of the DD-proton spectrum was conducted as well, using another piece of CR-39, to check if the emitted charged particles were subject to any significant plasma-energy losses. (b) Schematic drawing of the CPS, which uses a 7.6-kG permanent magnet (Nd-Fe-B) for dispersion of the charged particles. A narrow aperture (width = 2.0 mm) is used in front of the magnet for high-resolution measurements in the energy range covered by CPS [50 keV – 45 MeV (protons)]. The size of the magnet is minimized to allow mounting in a re-entrant module inside the OMEGA target chamber; the longest dimension is 28 cm, the gap width is 2 cm, and the weight is 160 pounds.

FIG. 2 (color). (a-c) d' and t' spectra measured simultaneously on three different OMEGA shots. The broadening of these spectra is due to the Doppler-effect and CPS-spectrometer response. (d) DD-proton spectrum measured for shot 31753 illustrates that the average energy is similar to the birth energy of 3.05 MeV, indicating that energy losses are negligible.

FIG. 3 (color). Differential cross section for the elastic n-^{2}H scattering (a), and elastic n-^{3}H scattering (b). The measured differential cross section for the elastic n-^{2}H scattering was normalized to a Fadeev calculated cross section that is accurate to about 1%, and that normalization factor, modified by the deuterium-tritium fuel ratio, was subsequently applied to the measured differential cross section for the elastic n-^{3}H scattering. Excellent agreement between the measured and Fadeev calculated n-^{2}H cross section indicates that the deconvolution process is providing high-fidelity data. Both the measured and *ab initio* NCSM/RGM calculated n-^{3}H cross sections (blue solid line) compare well with R-matrix calculations (red dashed line), considering the uncertainties.

Table I. Measured and calculated differential cross section for the elastic n-^{3}H scattering at 14.1 MeV. The NCSM/RGM calculation is considered to be accurate to about 5%.

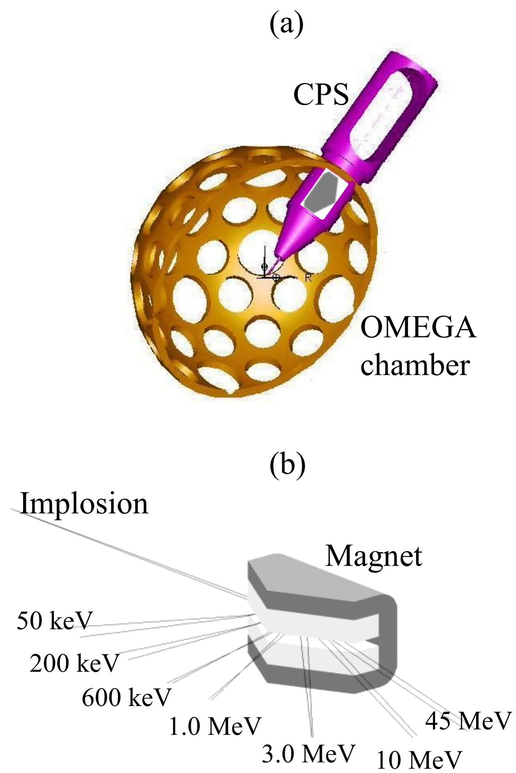
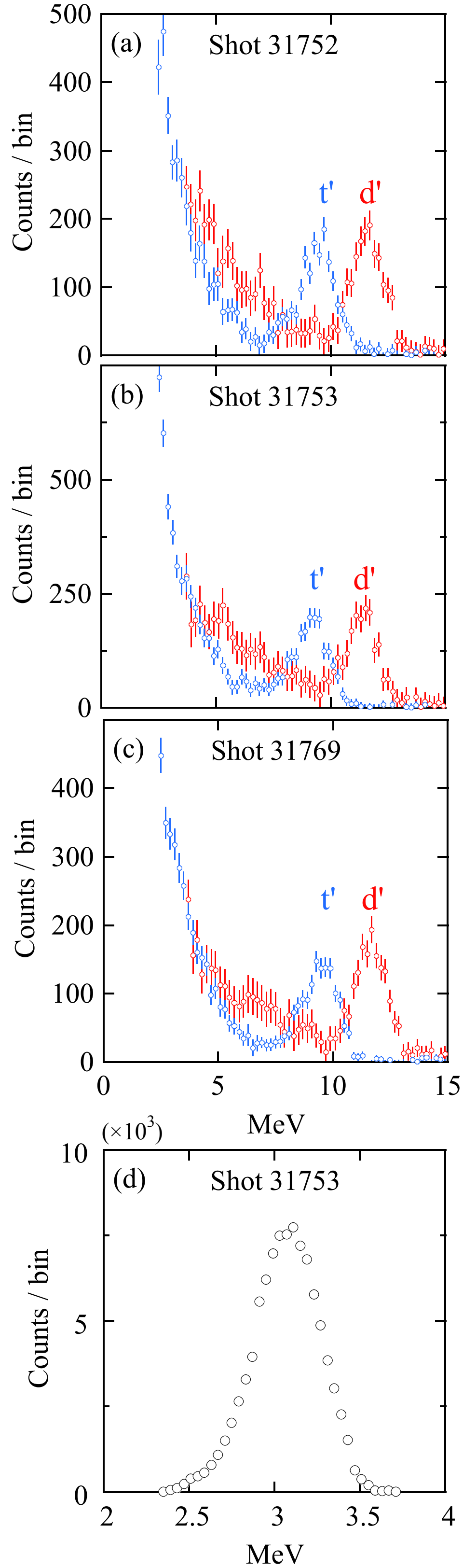
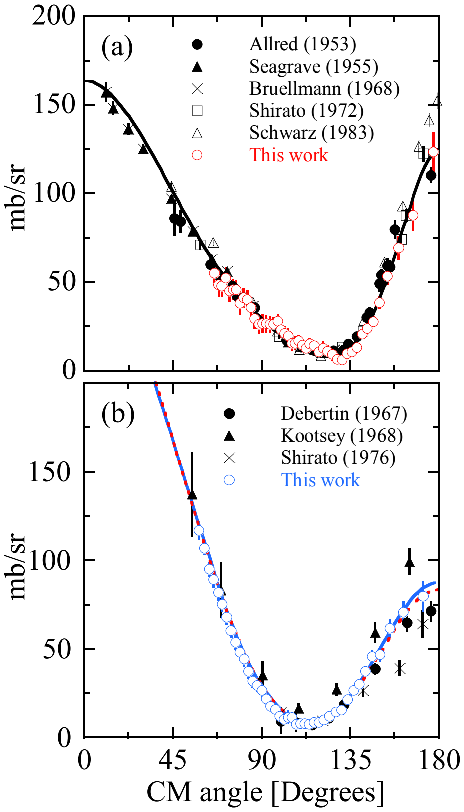

(a)
CPS
OMEGA
chamber
(b)
Implosion
Magnet
50 keV
200 keV
600 keV
1.0 MeV
3.0 MeV
10 MeV
45 MeV

Fig. 1



(a)
Shot 31752
t'
d'
Counts / bin
500
400
300
200
100
0
(b)
Shot 31753
t'
d'
Counts / bin
500
250
0
(c)
Shot 31769
t'
d'
Counts / bin
400
300
200
100
0
0
5
10
15
MeV
(×10^3)
10
(d)
Shot 31753
Counts / bin
5
0
2
2.5
3
3.5
4
MeV

Fig. 2.



200
150
100
50
0
mb/sr
(a)
Allred (1953)
Seagrave (1955)
Bruellmann (1968)
Shirato (1972)
Schwarz (1983)
This work
(b)
Debertin (1967)
Kootsey (1968)
Shirato (1976)
This work
0
45
90
135
180
CM angle [Degrees]

Fig. 3.

Table I

CM angle [degrees]	Measured (This work) [mb/sr]	Error [mb/sr]	Calculated (NCSM/RGM) [mb/sr]
58.6	116.7	4.4	119.3
61.2	106.6	3.3	109.9
63.7	94.7	3.5	101.1
66.1	88.8	3.6	93.1
68.3	81.6	3.7	85.6
70.5	75.0	3.9	78.7
72.6	67.8	3.7	72.1
74.7	60.3	3.6	65.9
76.8	53.4	3.5	59.9
79.0	48.1	3.2	54.1
81.2	44.0	3.2	48.5
83.4	37.1	3.3	43.2
85.7	31.5	3.1	38.2
87.9	29.4	2.8	33.4
90.3	26.3	2.9	29.1
92.6	21.7	2.9	25.1
94.8	17.5	2.7	21.6
97.1	15.7	2.5	18.5
99.3	11.9	2.4	15.9
101.5	10.2	2.5	13.7
103.6	11.3	3.3	11.8
105.7	11.2	2.2	10.4
107.8	7.4	1.9	9.2
110.0	7.8	1.9	8.4
112.2	7.6	1.8	8.0
114.4	7.5	1.6	7.9
116.8	8.5	1.3	8.1
119.4	8.5	1.3	8.9
122.0	9.6	1.3	10.2
124.8	12.0	1.2	12.1
127.7	14.4	1.4	14.6
130.7	15.5	1.3	17.7
133.7	21.2	1.4	21.5
136.8	26.5	1.7	25.8
139.8	29.9	1.8	30.5
142.9	37.2	2.2	35.9
146.3	45.6	2.7	42.1
150.2	46.5	3.4	49.4
155.2	61.4	4.7	59.1
162.2	70.5	6.0	71.6
172.3	79.4	7.7	84.3