# Search for the signature of a halo structure in the p($^6$He,$^6$Li)n reaction

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Abstract: The elastic scattering p($^6$He,$^6$He)p and charge exchange reaction p($^6$He,$^6$Li)n have been measured in reverse kinematics with a secondary $^6$He beam. The angular distributions for these reactions were obtained. In the case of the charge exchange reaction, the ratio of the cross section for the Gamow-Teller transition to the ground state, and for the Fermi transition to the isobaric analog state is a measure of the relative strength of the two components of the exchange interaction, $V_{\sigma\tau}$ and $V_{\tau}$. This ratio is found compatible with existing systematics for stable T=1 nuclei, and no clear signature of a halo structure was found in the present data.

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The (p,n) charge exchange reaction has been a privileged tool to explore nuclear structure and nuclear interactions. This reaction is highly selective since only isobaric analog states (IAS) and Gamow-Teller (GT) resonances are strongly populated. The transition to the IAS is a $\Delta T=1$, $\Delta S=0$ non spin flip Fermi transition (F), whereas the excitation of GT resonances proceeds via a $\Delta T=1$, $\Delta S=1$ spin flip transition, induced respectively by the $V_\tau$ and $V_{\sigma\tau}$ components of the nucleon-nucleon interaction. In particular, these studies provide information on the spectroscopic strength of the states involved in these reactions, on the fraction of the sum rule exhausted by these transitions, and on the interactions $V_\tau$ and $V_{\sigma\tau}$.

The charge exchange reaction cross section can be compared to $\beta$ decay strength. This comparison for Fermi and GT transitions provides an essentially model independent means to extract the $V_\tau$ and $V_{\sigma\tau}$ interactions or more precisely their volume integral. A detailed review of this aspect can be found in ref. [1].

Both the ground state of $^6$He and its isobaric analog state in $^6$Li are expected to behave like halo states [2-5], therefore two reasons motivated this study: one is the possibility to get information on the interactions $V_\tau$ and $V_{\sigma\tau}$ in a low density region, the other is the sensitivity of the transition leading to the IAS with respect to the differences between the neutron and proton density distributions, as this was shown for example for a series of Sn isotopes [6]. Taking into account the significant effect observed for very small differences of radii in the Sn case, we would expect very strong effects in the case of the halo nuclei considered here. In this letter we report on the first study of the $V_{\sigma\tau}/V_\tau$ ratio for a transition between two halo states.

The secondary beams were produced by fragmentation of a 75 MeV/nucleon primary $^{13}$C beam, delivered by the GANIL accelerator, on a 1155 mg/cm$^2$ carbon production target, located between the two superconducting solenoids of the SISSI device [7,8]. The position of SISSI at the exit of the second cyclotron and at the entrance of the beam analysing $\alpha$–spectrometer allows for an improved collection of the produced secondary beams and for a better transmission to the different experimental areas. The total momentum acceptance of the system SISSI+$\alpha$-spectrometer was of the order of 0.6% and the angular acceptance was about 100 mr in the horizontal and vertical planes. This results in roughly one order of magnitude increase in beam intensity with respect to an ion-optical system without the SISSI device.

In this work, the magnetic rigidity of the alpha spectrometer was set at 2.82 T.m which corresponds to an average energy of 41.6 MeV/nucleon for $^6$He particles. At this rigidity, the total intensity of the secondary beams was of the order of $10^7$ pps in the acceptance of the system for a primary intensity of $2\times10^{12}$ pps. The intensity for the neutron-rich nuclei $^6$He and $^{11}$Be was of the order of a few percent of the total intensity, whereas the intensity for the nuclei closer to the stability valley such as $^7$Li and $^{10}$Be was around 1/5 of the total intensity. Data obtained with those beams will be presented elsewhere.

The p($^6$He,$^6$He)p and p($^6$He,$^6$Li)n reactions were studied using the energy loss spectrometer SPEG [9]. The reaction target was a 100µm thick polypropylene foil, $(CH_2)_3$. All the scattered particles were unambiguously identified in the focal plane of the spectrometer with an ionisation chamber and a plastic scintillator. The momentum and scattering angle were measured with two position sensitive drift chambers [10] placed 70 cm apart and located near the focal plane of the spectrometer. The elastic and inelastic scattering of the secondary beam were measured on $^1$H and $^{12}$C in the range $\theta_{lab}$=0.7°-6.0°, while the charge exchange reactions on $^1$H and $^{12}$C were obtained from $\theta_{lab}$=0.0° to 4.0°. In the latter case, the measurement down to 0° was possible due to the large difference in the magnetic rigidity between the beam and the ejectiles.

Elastic scattering data are of primary importance to determine the nuclear matter distributions, and the optical potential obtained from such data is an important input in the analysis of charge exchange reactions. Figure 1 shows a typical momentum spectrum for 41.6 MeV/nucleon $^6$He scattered on a $(CH_2)_3$ target. The two peaks correspond to the elastic scattering of $^6$He on $^{12}$C (right) and on the protons in the target (left). The latter is broadened due to the strong kinematic effects of the reaction. The energy resolution (FWHM) deduced from the elastic scattering on $^{12}$C is of the order of $\Delta E/E = 10^{-3}$. The angular resolution obtained from the width of the $^1$H peak, which is mainly determined by the angular width of the incident secondary beam, is estimated to be $\Delta\theta_{lab}$=0.3° (FWHM). These results are quite unique: for the first time in an experiment involving unstable secondary beams produced by nuclear fragmentation, the energy resolution was good enough to separate the ground state from inelastic states, without using other information such as the detection of the recoiling nucleus.

The absolute normalisation for the elastic scattering data on the protons in the $(CH_2)_3$ target was obtained from the elastic scattering on $^{12}$C which was measured simultaneously. Elastic scattering calculations for the system $^6$He + $^{12}$C using different optical model potentials [11-13] show that the angular distribution at forward angles is rather insensitive to the potential used. Therefore the absolute normalisation of the data was obtained from the measured cross section at the first maximum of the angular distribution. The uncertainty on the normalisation is of the order of 10%.

The experimental p($^6$He,$^6$He)p angular distribution is presented in Figure 2. We have analysed these data by using a standard parametrisation of the nucleon-nucleus optical model potential, with the parameters of Becchetti and Greenlees [14] (BG, dotted lines on the figure) and the so-called CH89 parameters [15] (dashed line). It should be noted that these parametrisations were adjusted to data for nuclei in the mass range A=40-209. The CH89 parametrisation reproduces better the overall shape of the angular distribution. This may result from the fact that this parametrisation is based on a more complete and accurate set of data. However, both calculated distributions are significantly higher than the data. It was possible to obtain a good description of the data by adjusting the parameters of the imaginary part of the CH89 potential (solid line), but we did not try to draw conclusions on the modification of the shape of the imaginary potential.

A momentum spectrum obtained for the reaction p($^6$He,$^6$Li)n at $\theta_{lab}=1°$ is shown in figure 3. The narrow peak in the middle of the spectrum corresponds to the stripping in the target of a secondary beam of $^6$Li$^{2+}$ to $^6$Li$^{3+}$. This peak provides a direct measurement of the angular width of the beam, which for the (p,n) measurements was about 1°. It also provides a measurement of the energy resolution of the beam without kinematic broadening, but including target inhomogeneities and energy straggling. The other peaks correspond, from right to left, to the (p,n) reaction populating the ground state and the 3.56 MeV state of $^6$Li. The latter is the isobaric analog state of the $^6$He ground state. This peak is broadened due to kinematic effects originating from the $\gamma$ decay of $^6$Li.

The expected (experimental) cross-sections for the Fermi and GT transitions can be written, following ref. [1], as a product of three factors

$$\sigma = \hat{\sigma}_\alpha\,(Ep,A)\;F_\alpha(q,\omega)B(\alpha) \qquad (1)$$

where $\alpha$ stands for F or GT. $\hat{\sigma}$ is a " unit cross section", depending on incident energy $E_p$ and target mass A. $F_\alpha(q,\omega)$ is a kinematical factor depending on the three-dimensional momentum transfer **q** and on the energy loss $\omega=E_X-Q_{gs}$, while $B(\alpha)$ is the $\beta$-decay transition strength, obtained from beta decay lifetimes.

Even without considering detailed features of the angular distributions, valuable information can be extracted from the ratio of the cross sections for the Fermi and GT transitions at 0°. Indeed, the ratio R defined by the relation

$$R^2=\widehat{\sigma_{GT}}/\widehat{\sigma_F} \qquad (2)$$

is closely related to the ratio of the volume integral $J_\tau$ and $J_{\sigma\tau}$ of the interactions $V_\tau$ and $V_{\sigma\tau}$ . It can be expressed as:

$$R=\left|\frac{J_{\sigma\tau}}{J_\tau}\right|\left(\frac{N_{\sigma\tau}}{N_\tau}\right)^{1/2}\approx\left|\frac{J_{\sigma\tau}}{J_\tau}\right| \qquad (3)$$

where $N_\tau$ and $N_{\sigma\tau}$ are distortion factors defined by the ratio of the plane wave to distorted wave amplitudes. At the present energy, the ratio $N_{\sigma\tau}/N_\tau$ is close to 1.

As shown is ref. [1], R can be determined experimentally and it is related to the 0° cross sections by the relation:

$$R^2=\frac{\sigma_{GT}(0°)(N-Z)}{\sigma_F(0°)B(GT)} \qquad (4)$$

A compilation of the ratio R obtained using equation (4) for N=Z+2 nuclei is shown on figure 4. The data corresponding to $^7$Li, $^{14}$C, $^{18}$O, $^{26}$Mg(p,n) reactions are from ref [16-19], and the calculation used the B(GT) values from Taddeucci et al [1]. The linear energy dependence of R is a well established behaviour observed for many stable nuclei [1] and has been attributed to the energy dependence of the $V_\tau$ potential. Brown, Speth and Wambach [20] have shown, using a meson exchange model, that this energy dependence arises essentially from a two pion exchange contribution to the $V_\tau$ potential.

The ratio R was also computed for the transitions measured in the present experiment, by applying equation (4). The value of B(GT) which is necessary to compute R was obtained from β decay lifetime measurements and is given in ref. [1] for the inverse β decay transition $^6$Li--->$^6$He. To be compared with the present experiment, it must be corrected by the spin factor $\frac{(2J_f+1)}{(2J_i+1)}$,where $J_i(J_f)$ refers to the initial (final) total angular momentum in the $^6$Li(n,p)$^6$He reaction.

It is known that the volume integral of the spin-isospin term $J_{\sigma\tau}$ measured for $^6$Li(n,p)$^6$He ground state (GT) transition is in good agreement with the values obtained for other systems [21], as well as with the theoretical predictions of Nakayama and Love [22]. The ratio R, or $\left|\frac{J_{\sigma\tau}}{J_\tau}\right|$ measured in the present experiment is in agreement with the systematic behaviour established for T=1 nuclei. This means that the isospin term $J_\tau$ also shows no deviation from the values obtained for stable nuclei. A deviation could have been expected due to the halo structure of the states which are involved in these transitions.

In summary we have measured elastic scattering of $^6$He nuclei on a proton target and p($^6$He,$^6$Li)n charge exchange reactions leading to the ground state and to the first L=0,T=1 state of $^6$Li. The analysis of the elastic scattering reveals that it is possible to reproduce the angular distribution, due probably to the limited angular range of these measurements, just by modifying the imaginary part of the optical potential. New measurements are necessary to cover a wider angular range and obtain more severe constraints on the optical potential.

It seems well established that the $^6$He ground state is a halo state, and there are also some indications that its isobaric analog has the same characteristics. The fact that the $J_{\sigma\tau}$ as obtained from the (n,p) reaction of previous studies is also in good agreement with the systematics, indicates that the transition strength between a standard ground state ($^6$Li) and a halo ground state ($^6$He) shows no anomaly. From the analysis of the (p,n) reactions, we conclude that the $J_\tau$ volume integral of the nucleon-nucleon effective interaction does not show any deviation from the systematics in this mass region. This indicates that the transition between two halo states also has standard strength, if we accept as granted that $^6$He and its IAS are halo states. Therefore, with this assumption, the presence or absence of a halo structure does not influence the transition strength in a (p,n) reaction. Possible explanations may be either that this assumption is wrong, or that the increase of the imaginary potential in such a system counterbalances the effect of the halo structure.

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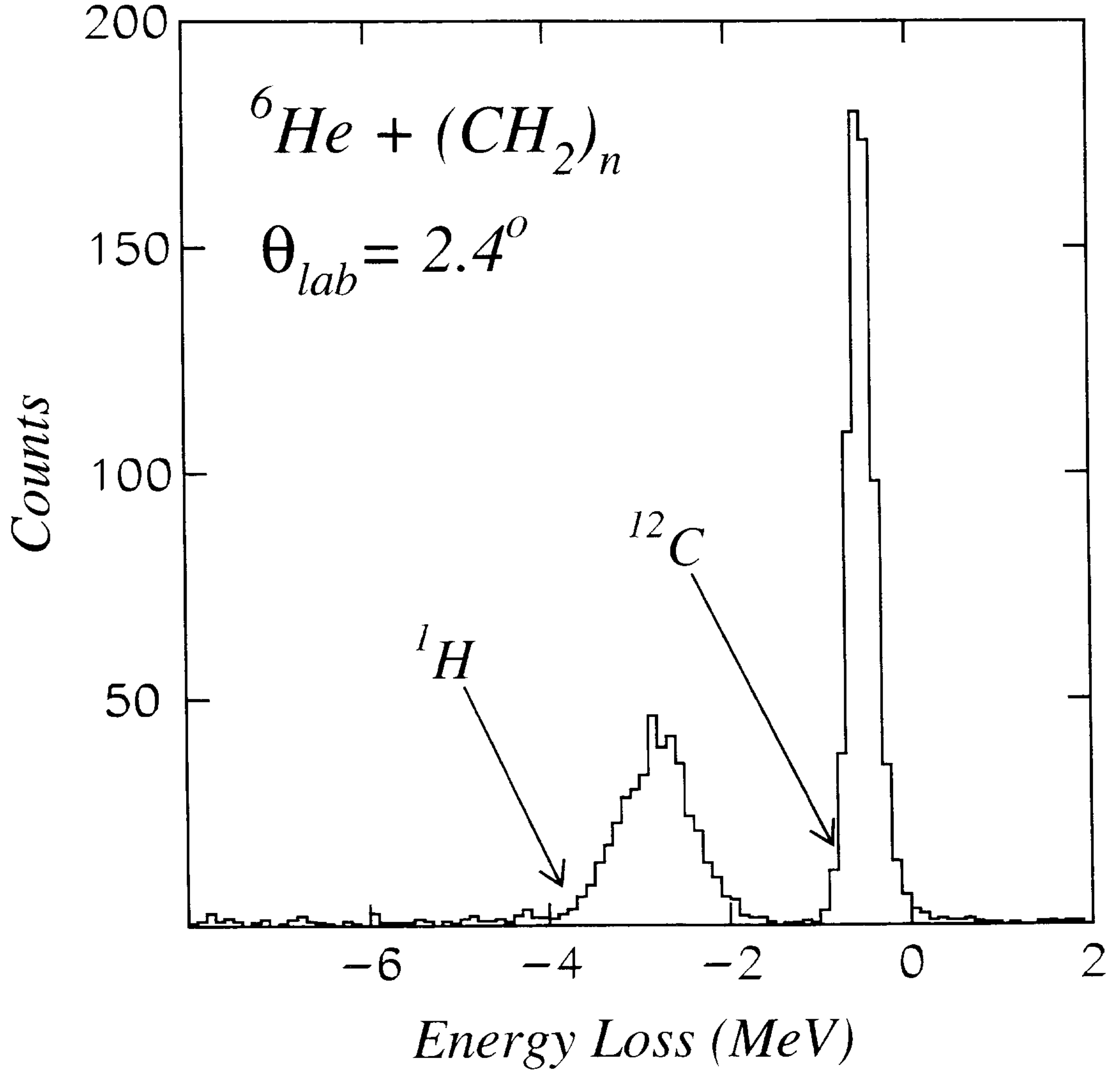
## Figure Captions

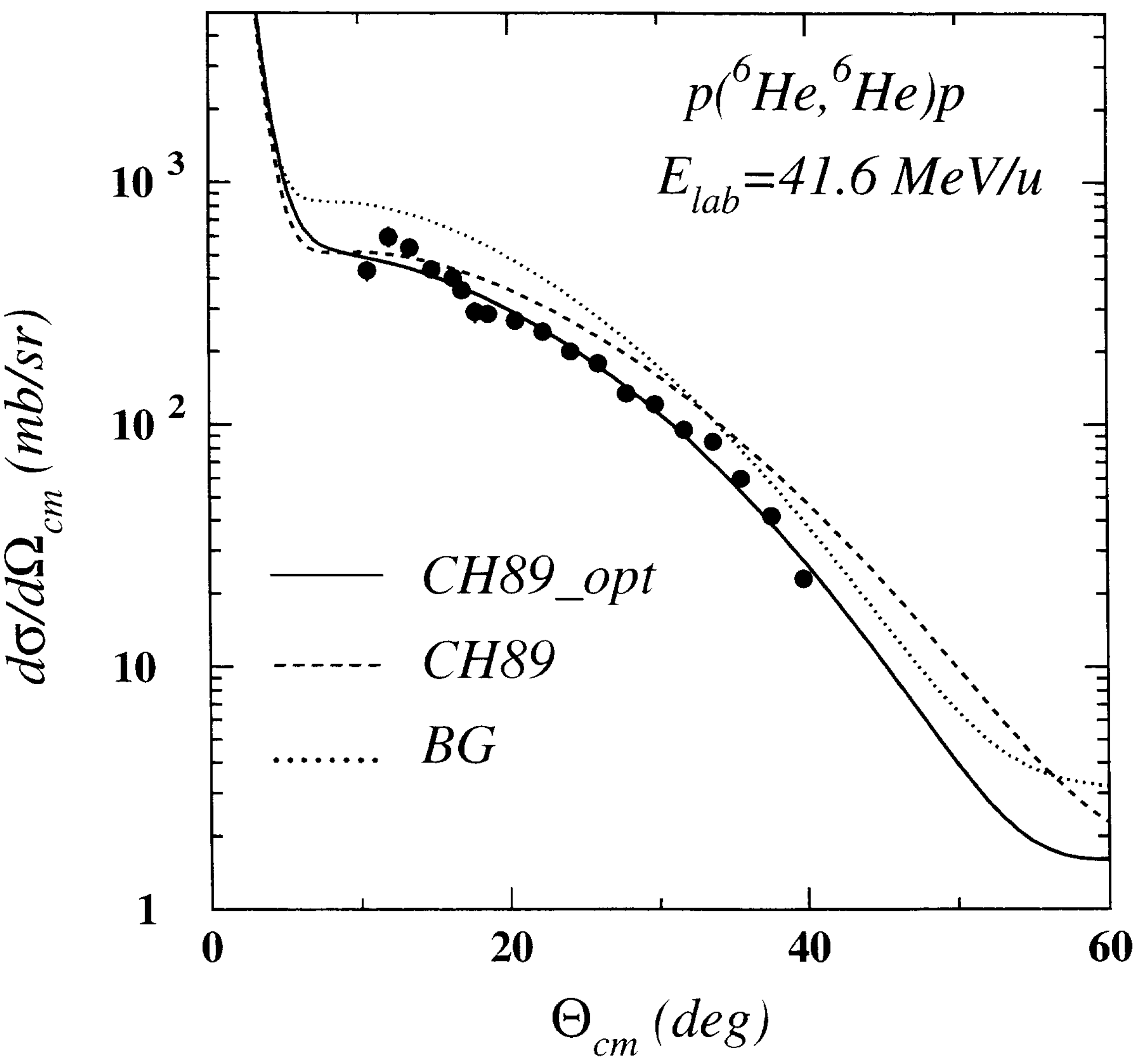
Fig. 1: Elastic scattering of $^6$He on a $(CH_2)_3$ target observed in the focal plane of the energy loss spectrometer SPEG

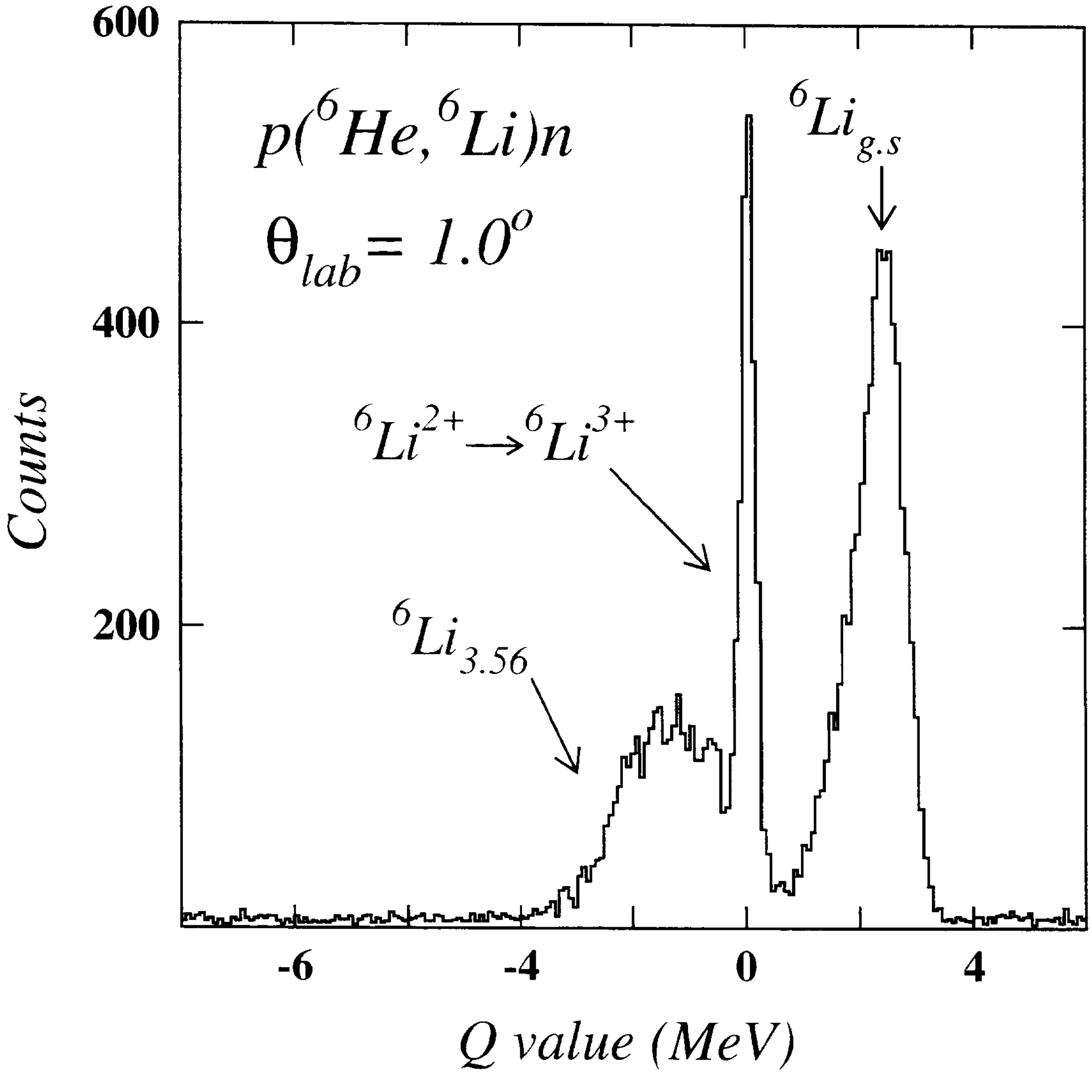
Fig. 2: Angular distribution for elastic scattering of $^6$He on $^1$H compared to various optical model potentials (see text)

Fig. 3: The charge exchange reaction p($^6$He,$^6$Li)n. The state to the right corresponds to the GT transition to the ground state of $^6$Li, the left one to the Fermi transition to the IAS state in $^6$Li. The sharp line corresponds to a small contribution of $^6Li^{2+}$ beam that is stripped to a 3+ charge state in the target.

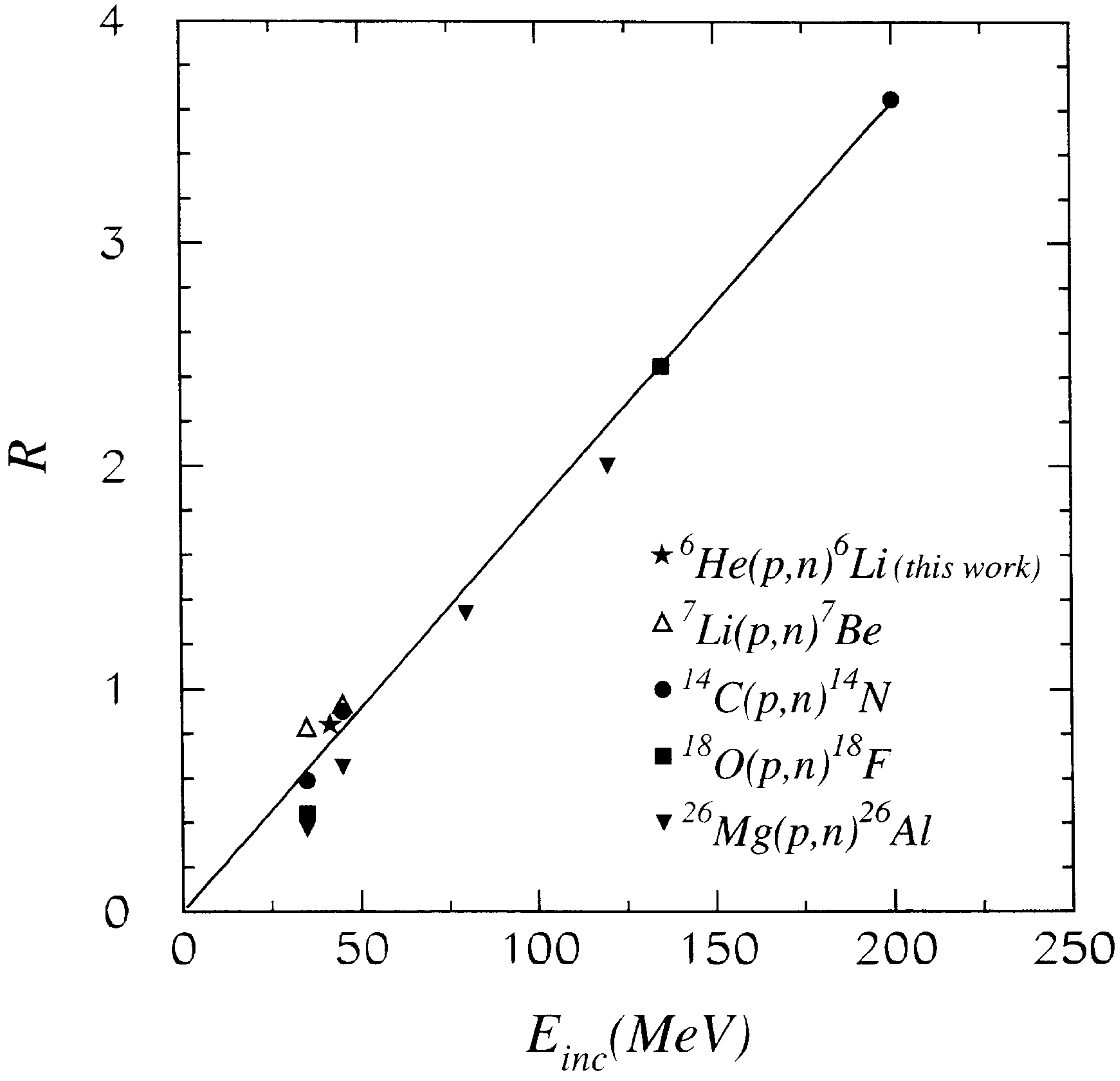
Fig. 4: Compilation of the reduced transition strength ratio R of GT and Fermi charge exchange transitions in light nuclei as a function of the incident energy of the proton.


$^{6}He + (CH_2)_n$
$\theta_{lab} = 2.4^o$
Counts
200
150
100
50
$^{12}C$
$^{1}H$
−6
−4
−2
0
2
Energy Loss (MeV)


p(⁶He,⁶He)p
E_lab=41.6 MeV/u
CH89_opt
CH89
BG
dσ/dΩ_cm (mb/sr)
Θ_cm (deg)
10³
10²
10
1
0
20
40
60



$p(^6He,^6Li)n$
$\theta_{lab}= 1.0^o$
$^6Li_{g.s}$
$^6Li^{2+}\rightarrow{}^6Li^{3+}$
$^6Li_{3.56}$
Counts
600
400
200
-6
-4
0
4
Q value (MeV)


R
0
1
2
3
4
0
50
100
150
200
250
$E_{inc}(MeV)$
★ $^{6}He(p,n)^{6}Li$ (this work)
△ $^{7}Li(p,n)^{7}Be$
● $^{14}C(p,n)^{14}N$
■ $^{18}O(p,n)^{18}F$
▼ $^{26}Mg(p,n)^{26}Al$