

Proton-tetraneutron elastic scattering

B.M. Sherrill and C.A. Bertulani*

*National Superconducting Cyclotron Laboratory,
and Department of Physics and Astronomy,
Michigan State University, East Lansing, MI 48824-1321, USA*

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Abstract

We analyze the elastic scattering of protons on a ${}^4\text{n}$ system. This was used as part of the detection technique of a recent experiment [1] to search for the ${}^4\text{n}$ (tetraneutron) as a bound particle. We show that it is unlikely that this process alone could yield the events reported in ref. [1], unless the ${}^4\text{n}$ has an anomalously large backward elastic scattering amplitude.

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*Electronic address: sherrill@nscl.msu.edu, bertulani@nscl.msu.edu

The possible existence of the tetraneutron has been discussed theoretically by numerous authors already in the 1960's (see refs. [1–3] and references therein). Numerous experiments have been performed with negative results ([1–3] and references therein). However, in a recent experiment [1], the existence of bound neutron clusters was studied by fragmentation of intermediate energy (35 MeV/nucleon) ^{14}Be nuclei. As described in ref. [1], the data analysis was confined (for technical reasons related to the detector response) to 11-18 MeV/nucleon. The fragmentation channel $^{10}\text{Be} + ^4\text{n}$ was observed and the ^4n system was tentatively described as a bound tetraneutron system.

Theoretical attempts have failed to find the mechanism for the ^4n binding. Ref. [2] concluded that a strong four-nucleon force is needed to bind the tetraneutron. This force would unreasonably bind ^4He by about 100 MeV. Ref. [3] showed that a model of the tetraneutron based on two dineutron molecules is also not likely to yield a bound system. Further, ref. [4] showed that if the ^4n would form a bound system it would indeed look like two widely separated dineutrons, with rms radii between 7.3 fm and 10.3 fm. However, these conclusions were based on a significant change of presently adopted NN potentials.

In this brief report we point out a puzzle in the experimental measurement [1]. We calculate the elastic proton-tetraneutron cross section and show that it is surprising that the experimental technique used in ref. [1] could identify a bound ^4n based on this reaction. In the original experimental paper the ^4n was identified by the recoil imparted on a proton target. In particular ^4n were identified by an anomalous large backward recoil of the proton. We claim that, due to the loosely bound character of the tetraneutron (if it existed) this anomalously large proton recoil is unlikely, as the elastic cross section for the proton-tetraneutron system drops many orders of magnitude for large scattering angles. If the data of ref. [1] is correct, they indicate an anomalously large backward angle cross section or that other processes are contributing.

To calculate the proton- ^4n scattering cross section one needs the p- ^4n phase-shifts $\delta_{l\pm}$, or an optical potential, both of which are of course unknown. One can construct one theoretically using several recipes. For simplicity we will use here the M3Y interaction [6] to construct $U_{\text{real}}(r)$. The imaginary part of the potential is taken as $U_{\text{imag}}(r) = \lambda U_{\text{real}}(r)$. We adopt a very conservative value, $\lambda = 1$, for simplicity. The input in this calculation is the tetraneutron density distribution $\rho(r)$ which is of course unknown. We assume that if the tetraneutron exists it has a large rms radius, due to its loosely-bound character. We

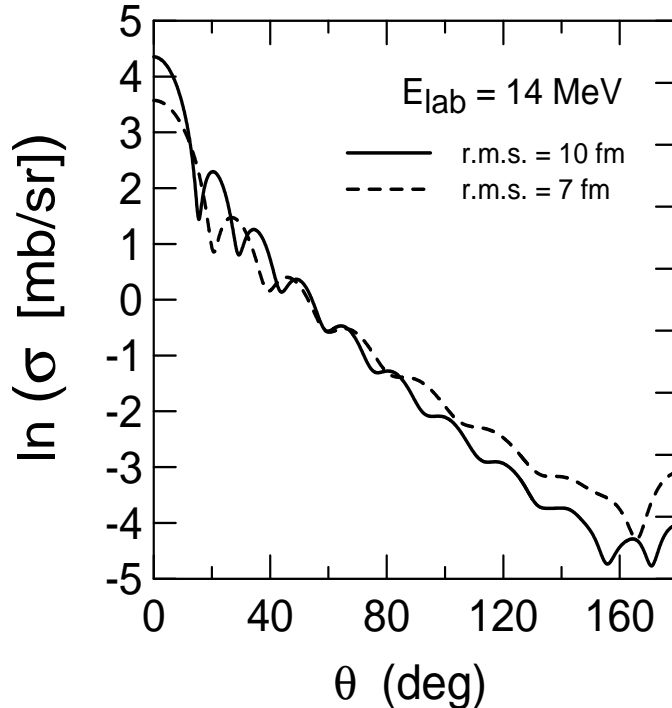


FIG. 1: Proton- ${}^4\text{n}$ elastic scattering at $E_p = 14$ MeV. The dashed (solid) line assumes a ${}^4\text{n}$ matter density distribution with an rms radius of 7 fm (10 fm).

take a one-body density distribution with rms radii of 7 fm and 10 fm, respectively [5]. This simulates the small binding energy of the system.

The result of the calculation is presented in figure 1, for $E_p = 14$ MeV and a ${}^4\text{n}$ -system with rms radii equal to 7 fm (dashed line) and 10 fm (solid line), respectively.

In figure 2 we show the kinematics of the ${}^4\text{n}$ -proton scattering in the laboratory. In particular, we show the proton energy as a function of its backscattering angle in degrees, in the kinematical allowed region. In the laboratory, the protons would have recoil energies in the interval $E_p = 21 - 38$ MeV, for scattering angles between 95 - 180 degrees. This is shown by the solid line in figure 2. The dashed line is the respective ${}^4\text{n}$ energy.

For proton recoil energies in the interval $E_p/E_n = 1.4 - 2.6$ we get a total elastic cross section (from figure 1) of about $3.5 \mu\text{b}$, assuming a ${}^4\text{n}$ size of 7 fm (a ${}^4\text{n}$ size of 10 fm yields a 10 times smaller value).

The intensity of ${}^{14}\text{Be}$ in the experiment of ref. [1] is 130 particles per second. Assuming a ${}^4\text{n}$ production cross section of 1 mb, as estimated in ref. [1], as an upper estimate and

a carbon target with 275 mg/cm^2 , we obtain $1.8 \times 10^{-2} \text{ }^4\text{n/s}$. The density of protons in the target can be estimated as $n = 10^{24}/\text{cm}^2$. For a cross section of $3.5 \text{ } \mu\text{b}$ one thus gets a counting rate of 10^{-9} scattered protons per second. The overall (geometry + response of the detectors) detector efficiency in the experiment is of the order of 10%. This yields approximately 10^{-4} events per week. The experiment of ref. [1] claims 6 events in a one week run. There is a factor of 10^4 more events than expected from an optimistic estimate.

The estimates presented above show that the results of the experiment can not be explained as arising from elastic scattering unless there is an anomalous large backscattering in the $^4\text{n+p}$ system. We think that the ^4n model used in our calculations should yield an order of magnitude estimate of the distribution of the backscattered protons. It is well known that the elastic scattering cross section decreases exponentially with the diffuseness of the system. For a system of size R and diffuseness a , the differential cross section scales as (see, e.g., ref. [8]) $d\sigma/d\Omega \sim [J_1(qR)/q]^2 \exp(-qa)$, where $q = 2k \sin(\theta/2)$ is the momentum transfer. Thus, the slope of the cross section in figure 1 is due almost entirely to the diffuse character of the ^4n system. This behavior is universal and would not change with a better description of the potential. In the absence of the Coulomb interaction and other effects, the peak at forward angles yields the total cross section by means of the optical theorem. Its magnitude is due to the overall size of the system. Thus, the only parameter of interest in this case is the diffuseness of the tetraneutron, which determines the backward/forward cross section ratio.

One possible scenario to explain the events seen in ref. [1] is that the neutrons do not scatter from the ^4n as a whole, but from a smaller neutron cluster inside the ^4n system. If the dineutron exists, it might be less diffuse than the ^4n system. This in consequence could lead to a larger scattering cross section of the protons towards large angles. However, this would also lead to scattered protons with smaller energy. Another possible effect, short-range correlations, which imply large momentum components inside the ^4n system, are also ruled out as they must be a small component of the total ^4n wavefunction. We thus conclude that both of these effects do not help in explaining those events.

One should also expect that additional effects probably imply an even smaller cross section for the ^4n (or ^2n)-p elastic scattering at large angles. Since ^4n is loosely bound there will be a large absorption from the elastic channel due to the inelastic events which disrupt the ^4n system. The larger the scattering angle, the larger the momentum transfer and the smaller

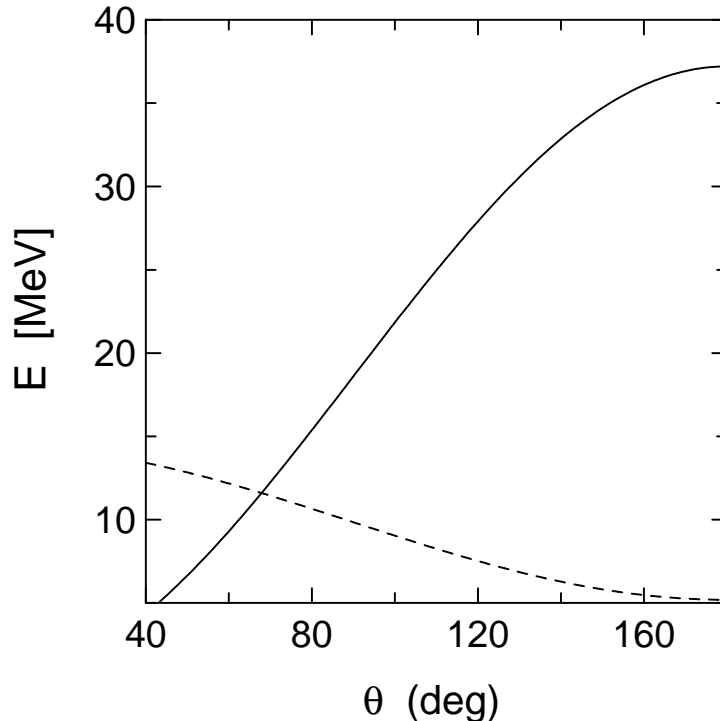


FIG. 2: Kinematics of the ${}^4\text{n}$ -proton scattering in the laboratory. The solid line shows the proton recoil energies in the interval $E_p = 21 - 38$ MeV, for scattering angles between $95 - 180$ degrees. The dashed line is the respective ${}^4\text{n}$ energy (per nucleon).

the cross section will be. This effect was not included in our calculations and would pose an even worse scenario for the detection of elastic scattered ${}^4\text{n}$ by proton backscattering.

Our calculations suggest that other processes besides elastic scattering are required to sustain the bound ${}^4\text{n}$ interpretation of the events observed in ref. [1]. A possible case would be the inelastic scattering on protons of very weakly bound systems [9]. However, to produce $\theta_{cm} > 100^\circ$ recoils, the ${}^4\text{n}$ system must interact as a composite object. Given its weak binding, it is unlikely an inelastic interaction could produce a high energy proton.

In conclusion, we have shown that elastic scattering cannot be used to detect a bound ${}^4\text{n}$ nucleus [1]. If the ${}^4\text{n}$ system exists it has to be very weakly bound and it will also be a very large and diffuse system. It is very unlikely that such a system can scatter protons at angles of $\theta > 90^\circ$.

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