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Experimental search for condensed nuclear states*

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We have studied and made use of backward (180°) elastic scattering of 600 and 800 MeV protons as the experimental tool to search for the presence of nuclear states of very high binding energy, suggested by Feenberg and Primakoff and by Lee and Wick. This method, tested on a variety of targets, found no evidence for condensed nuclei (of 100 mb cross section) at a level of 10^{-8} per target nucleus.

[NUCLEAR REACTIONS Upper limit to fraction of condensed nuclei in Be, C, Cu, Ta, Au, Pt targets by measurement of backscattering of 600 and 800 MeV protons.]

I. INTRODUCTION

Feenberg and Primakoff[1] and recently Lee and Wick[2,3] have speculated on the possibility of new condensed states of nuclear matter containing very highly bound nucleons. Lee has emphasized the possible creation of these states in collisions of heavy nuclei. This and other attempts have been reported[4,5] with negative results. Here we take the view common to exotic particle searches that if a stable state is possible, it may already exist undetected in ordinary matter. This experiment is designed to begin to put limits on the possible abundance of condensed states. Such states, with nuclear binding energies comparable to the nucleon rest mass, would differ greatly from ordinary nuclei in that high energy proton scattering would be highly coherent even at large momentum transfers. The elastic backscattering of protons from ordinary nuclei at high momentum transfers is not known theoretically or experimentally, but at bombarding energies much larger than ordinary nuclear binding energies the probability of the whole nucleus recoiling is expected to be very small. Thus by looking experimentally in this kinematic region we would expect negligible background of protons from proton-nucleus scattering.

It is entertaining to speculate on targets that are "most likely" to contain condensed nuclei.[5] In our present search, and to test the sensitivity of our method, we have simply used easily available materials (Be, C, Cu, Ag, Ta, Au, and Pt). However, the Au foils employed were irradiated with $\approx 3\times 10^{17}$ 300 GeV protons at Fermilab[6] while the Pt target was part of a Princeton-Penn Accelerator[7] internal target that had been irradiated with 3 GeV protons for many years. (Here the possibility exists that condensed states could have been formed in the collision of recoiling target nuclei.)

II. METHOD

In order to achieve high sensitivity in a search for condensed states we chose to use the high proton flux available at LAMPF ($\approx 10^{13}\, p$/sec) hoping that background at our apparatus, located close to the primary beam and target, would be sufficiently small. Under good beam steering conditions, and by using small thin detectors, this goal was achieved.

The desired beam energy, less than $m_p c^2$ but sufficiently large (600, 800 MeV) so that elastically backscattered protons from ordinary nuclei would be negligible, also made LAMPF an ideal choice. Since it was our intent to keep the scale of our apparatus commensurate with the low probability of observing condensed nuclei we designed our experiment to use part of the LAMPF beam line as our experimental apparatus. This decision allowed for rapid completion of the experiment although at reduced sensitivity and flexibility.

Figure 1 shows our apparatus set up in line B at LAMPF. The bending magnet (LB-BM-05) is part of the LAMPF proton line but simultaneously served us as the momentum analyzing magnet for particles *backscattered* from targets directly downstream. The only change made in the beam line was the replacement of a section of the vacuum chamber within the magnet with one that possessed a 2.54×10^{-3} cm Havar exit window for backscat-

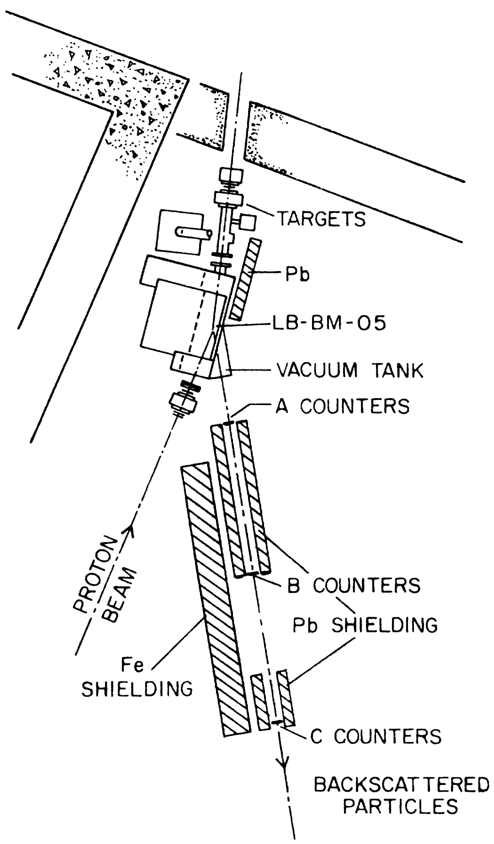

FIG. 1. Location of experimental apparatus in the B tunnel at LAMPF. Particles backscattered from targets located in the primary proton beam are bent out by the beam bending magnet into a three-element scintillator telescope ABC.

tered particles. The targets were mounted on a LAMPF beam profile monitor activator normally used for beam tuning diagnostics, but used by us to insert up to four targets remotely. Our basic detector (Fig. 2) consisted of a scintillation counter telescope composed of three triplet elements $A \equiv (A_1A_2A_3)$, $B \equiv (B_1B_2B_3)$, and $C \equiv (C_1C_2C_3)$ separated in space to allow for time of flight measurements. The first element A_1 was a 2.54 cm$\times$2.54 cm$\times$0.079 cm scintillator made thin to reduce production of electrons (and protons) from background γ rays (and neutrons) incident on it. All other scintillators in the AB telescope were 2.54 cm$\times$2.54 cm$\times$0.16 cm except for B_3 which was 2.54 cm$\times$2.54 cm$\times$0.95 cm, the 0.95 cm thickness allowing for improved timing and pulse height resolution. The elements of C were 4.45 cm$\times$5.08 cm$\times$0.16 cm scintillators. The scintillation counters were shielded locally with 5 to 10 cm of lead bricks; a 61 cm thick iron and concrete wall shielded A and B from particles spraying along the beam line.

Figure 3(a) shows a time of flight spectrum taken at a spectrometer angle corresponding to 890 MeV/c backscattered particles when the incident beam momentum was 1463 MeV/c (800 MeV). At this momentum one can clearly see peaks corresponding to (1) relativistic electrons produced from γ rays striking the first scintillator (A_1), the vacuum chamber window, or the air in between them, (2) protons, (3) deuterons, and (4) tritons.

Figure 3(b) shows a typical pulse height distribution in B_3 showing the minimum ionizing pulses and the larger pulses from p, d, and t. From data such as these the proton yield is extracted from the γ ray, deuteron, triton, and knock-on proton background.

As the telescope is moved to spectrometer angles corresponding to higher backscattered momenta, the γ background-proton separation cannot be accomplished using the AB time of flight. Because our apparatus axis intersected apparatus located in a neighboring proton beam line (not shown in Fig. 1) we were not able to use a sufficiently long flight path to allow clean γ background-proton separation. To reduce this background we employed an atmospheric pressure SF_6 Cherenkov counter to identify hard electrons with $(1 - v^2/c^2)^{-1/2} > 30$. In addition, one radiation length of lead and a small permanent (sweeping) magnet (0.4 kG m) were placed just after the B triplet to absorb, scatter out, and bend the copious soft electrons. Together these methods produced a background reduction of approximately 300.

Figure 4(a) shows the time of flight spectrum in the AB telescope set at the elastic angle (1219 Mev/c, 600 MeV incident). Both a γ background peak and a long time of flight spread of protons resulting from neutron interactions are apparent. Figure 4(b) shows the same spectrum for those events for which the Cherenkov counter fired. Figure 4(c) shows the time of flight spectrum in the AC telescope when the Cherenkov counter, the lead absorber, and the bending magnet are employed to eliminate γ background. The time of flight scale for this spectrum has been scaled to compare with the shorter AB time of flight. From spectra such as these the sensitivity for observing condensed states is extracted.

In order to determine whether protons can be elastically backscattered from ordinary nuclei it is necessary to study yields out to the highest possible momenta. Figure 5 shows the yield of protons as a function of their kinetic energy (plotted at the nominal value of the center of the energy acceptance of the spectromenter) for a typical target Be. If this yield is extrapolated linearly on a semilog plot to the energy for elastic backscattering we would expect only 10^{-8} protons per day for a typi-

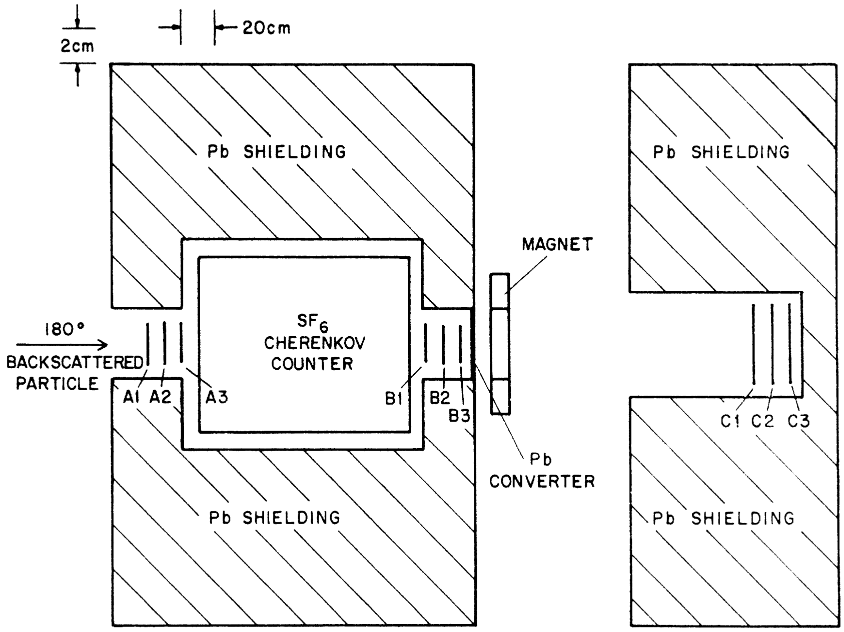

FIG. 2. More detailed sketch of the experimental apparatus.

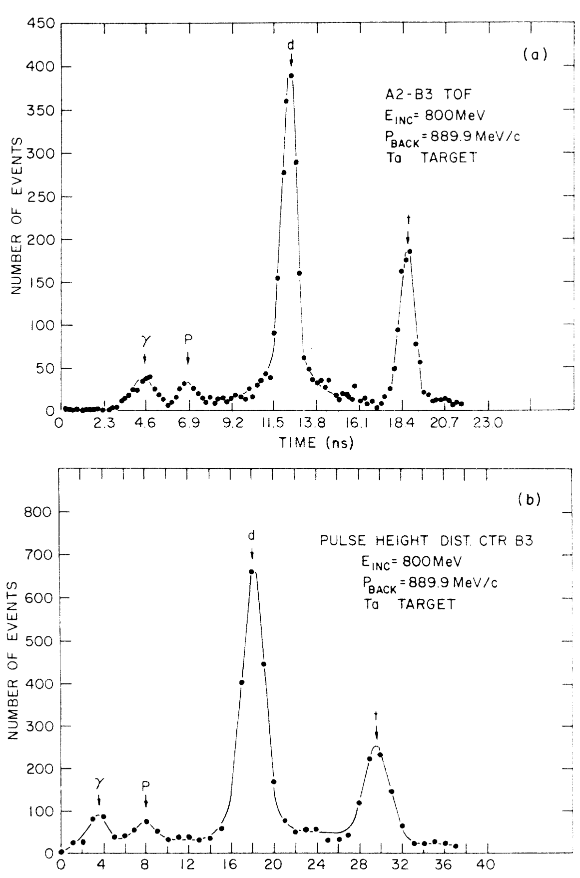

FIG. 3. (a) Number of backscattered events vs time of flight in the AB telescope. (b) Number of events vs pulse height in scintillator counter $B3$.

cal flux of $5\times 10^{12}\,p/\mathrm{sec}$. Actually we expect the value obtained from this extrapolation to be an overestimate. Proton backscattering from normal nuclei was not the limit to the sensitivity of this experiment.

The solid angle of the AC spectrometer was 6×10^{-5} sr. Its momentum resolution (~5% full width at half maximum), as determined from first order optical calculations, is almost constant over a symmetric momentum interval about the mean spectrometer momentum P_0. At a spectrometer angle corresponding to elastic backscattering from an infinitely heavy nucleus, the mass range covered extends down to 150 proton masses (m_p) at 800 MeV incident kinetic energy, and to $135 m_p$ for 600 MeV incident kinetic energy. At the spectrometer angle corresponding to elastic backscattering from a nucleus with $63 m_p$, the mass range covered is from $44 m_p$ to $109 m_p$ at 800 MeV incident energy. Thus a large range of possible masses for the condensed nucleus is spanned in this experiment. Runs on Be, C, Cu, and Ta were carried out at 600 MeV; those with Ag, Ta, Pt, and Au were carried out at 800 MeV.

III. RESULTS

We have found no evidence for peaks above background corresponding to elastic backscattering. Further, all of the targets studied have similar backgrounds in the elastic region. We therefore conclude that the events in this region are background events and that we have found no evidence for condensed states in these samples.

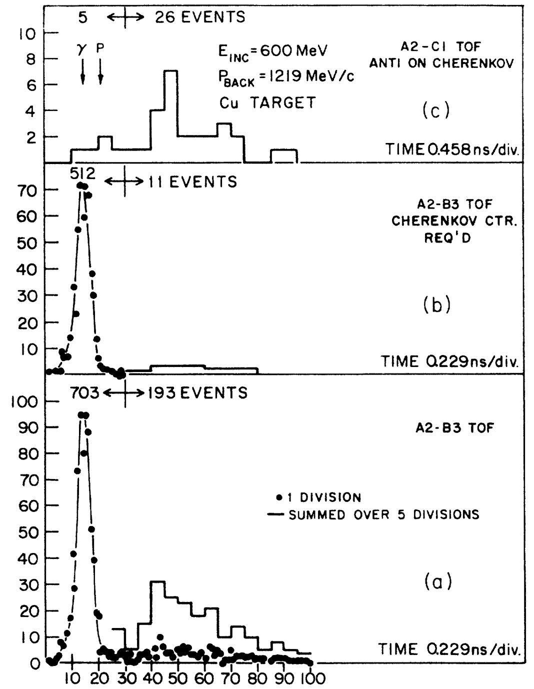

FIG. 4. Time of flight spectra for a spectrometer angle corresponding to elastic backscattering (1219 MeV/c). (a) Spectrum in the AB telescope; (b) spectrum in the AB telescope of particles triggering the Cherenkov counter; (c) spectrum in the AC telescope after Cherenkov counter, lead absorber, and bending magnet are employed to reduce γ-ray induced background.

We parametrize our results by specifying the 90% confidence level upper limit number of condensed nuclei per normal nucleus $\equiv S$. To do this we must arbitrarily assign a cross section to this process. If we choose to use σ(abnormal) = πR^2 where $R = R_0 A^{1/3}$ and R_0 (= 0.3 fm) is of the order of the nucleon repulsive core, the cross section would be 100 mb at $A = 216$, which is smaller than ordinary nuclear cross sections at these energies. For simplicity in presenting the data, we shall arbitrarily use this value as our single reference cross section for all masses, assuming isotropic scattering. Table I shows our results for S.

IV. COMMENTS

This experiment was debugged as a parasite experiment with apparatus located in an unshielded area inside the beam tunnel. With few allowable entries little apparatus improvement could be carried out and accelerator procedure imposed limits on target position and target thickness. Shielding was minimal and detector size small. About 9 h of running time were obtained for each target. With a carefully designed experiment, a factor of 1000 increase in sensitivity can be readily achieved.

Thus the LAMPF installation could yield sensitivities of ~10^{-11} condensed nuclei (of 100 mb cross section) per ordinary nucleus if interesting samples were to be studied.

A parallel purpose of this experiment was to push measurements of backscattering of protons from nuclei at high momentum transfer q^2 and low energy transfer to the very low limits possible with modern high intensity beams.

The last column of Table I also gives the two standard deviation upper limit to the differential cross section for the scattering of protons from the ordinary target nuclei into the spectrometer energy acceptance ΔE. The listed values are obtained from the formula: $\sigma(180°) = 100(S/4\pi\Delta E)$ mb/sr. The energy bands studied are determined from the spectrometer resolution. For 800 MeV incident energy the bands are 800-765 and 761-700 MeV. For 600 MeV the bands are 600-572 and 570-522 MeV. The ΔM mass ranges in Table I are computed from these bands. Typical upper limits are in the pb(sr MeV)$^{-1}$ range. Our observation at other backscattered momenta of the production of protons, deuterons, and tritons at 180° with very high values of rapidity ($x = p/p_0$) is in preparation for publication.

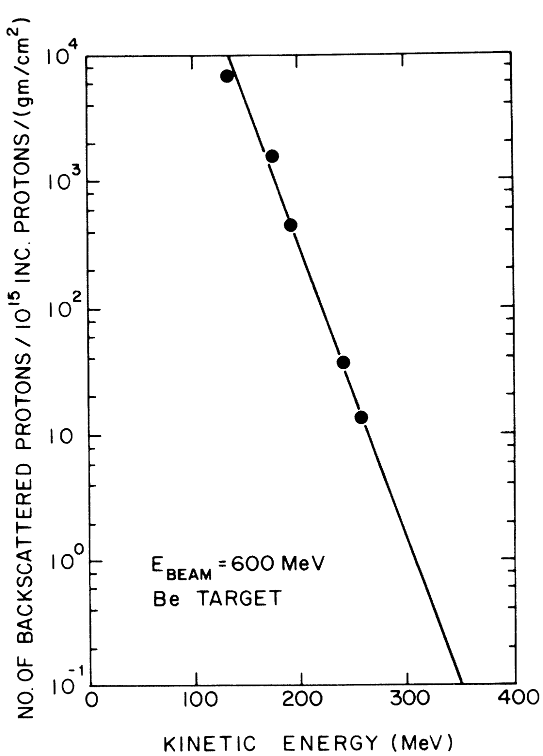

FIG. 5. Yield of protons vs backscattered kinetic energy setting of spectrometer.

TABLE I. Two standard deviation limits to S, the number of condensed nuclei of 100 mb cross section per target nucleus, and to the differential cross section for backward p-nucleus scattering. ΔM is the spectrometer mass resolution. Column 6 gives the two standard deviation upper limit to the differential cross section for elastic backscattering from the normal target nuclei.

E_{incident} (MeV)	ΔM (GeV)	Target	Incident protons ($\times 10^{17}$)	S ($\times 10^{-8}$)	pb(sr MeV nucleus)$^{-1}$
800	150–∞	Au	1.09	8.7	20.6
800	150–∞	Pt	1.15	8.9	21.4
800	44–109	Au	1.31	21.1	27.9
800	44–109	Pt	1.14	15.9	20.6
800	44–109	Ta	0.19	85.5	11.1
600	135–∞	Be	0.28	0.98	···
600	135–∞	C	0.24	1.06	···
600	135–∞	Ta	1.11	13.75	40.6
600	135–∞	Cu	0.95	2.78	···
600	39–94	Be	0.17	0.77	···
600	39–94	C	0.91	0.56	···
600	39–94	Ta	1.42	9.28	15.1
600	39–94	Cu	1.20	5.92	19.1

V. ACKNOWLEDGMENTS

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[6]We wish to thank J. Sanford and D. Theriot for their co-operation in the irradiation of an Au foil at Fermilab.

[7]We wish to thank Professor M. White for the loan of the former P. P. A. target.